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guided-inquiry based laboratory instruction: investigation of critical thinking skills, problem solving skills, and implementing student roles in chemistry

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Guided-inquiry based laboratory instruction: Investigation of critical thinking skills, problem solving skills, and implementing student roles in chemistry

by

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DEDICATION

To my Mother

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CHAPTER 1

GENERAL INTRODUCTION

Laboratory instruction has an important place in the teaching and learning of science. Especially at the college level, laboratory instruction gained prominence in the early nineteenth century due to a growing interest in the importance of practical work and experimentation in the natural sciences (Nakleh, Polles, and Malina, 2002; Hofstein, 2004). As stated by Lunnetta, Hofstein and Clough (2007), worthwhile laboratory practical experiences lead to a meaningful learning of science. Laboratory experience is considered an essential component of science teaching (Kirschner, and Meester, 1988).

Review of the research on the past role of laboratory instruction emphasizes a lack of research-based evidence on the effectiveness of chemistry laboratories in enhancing students' subject matter knowledge and cognitive skills (Hofstein, and Lunnetta, 1982; Hofstein, and Mamlok-Naaman, 2007). Criticism has been primarily directed at the traditional approach to laboratory instruction, which is mainly instructor-centered (Hodson 1988; Toothacker, 1983). However, the traditional approach provides students an opportunity to experience chemistry hands on, manipulate the equipment, and actually verify concepts (Bates, 1978). This situation can be argued to be better than the situation in which chemistry instruction is provided to students with (a) no laboratory component, (b) the only laboratory component is in the form of instructor demonstrations during the lecture, or (c) laboratories are optional, leaving it to student discretion to pursue or not to pursue a chemistry laboratory course along with the lecture component of chemistry.

Recent initiatives in the laboratory curriculum have encouraged an inquiry-based approach to learning and teaching in the laboratory. It has been argued that laboratory instruction should not just be hands-on, but it should portray the essence of inquiry through the process of experiential learning and reflective engagement in collaboration with peers, facilitated by the instructor. In summary, a student-centered active learning approach may be an effective way to enhance student understanding of concepts in the laboratory (Tobin, 1990; Weaver, 1998; Spencer, 1999; Hofstein, 2004; Hofstein, Navon, Kipnis, and Mamlok-Namaan, 2005).

It is difficult to separate experiments in chemistry from thinking skills on chemistry concepts. Students may learn about numbers, and theoretically manipulate variables in their homework assignments, but when it comes to physical observations and performing chemical reactions, the laboratory is a unique medium to enhance student perceptions in chemistry and may contribute to a positive student attitude towards the subject as well as enhance student experiences as learners through practice (Lazarowitz, and Tamir, 1994; Clackson, and Wright, 1992; Blosser, 1983).

Technological advances have also impacted laboratory instruction. Technology aids chemistry instruction when students are able to visualize microscopic behavior during chemical processes in the form of animations and simulations (Tversky, 2001; Gredler, 2004). Experimentation enables students to experience the changes occurring during a physical process or chemical process hands-on, but those are macroscopic behaviors (Kelly, 2005; Falvo, 2008). The blend of technology and laboratory experiments could turn into a boon if the technology is implemented appropriately in sync with the lecture and the laboratory component of a chemistry course (Kelly, and Jones, 2005). However, technological innovations are not a replacement for laboratory experiences as they cannot exactly simulate reality. At any point even the slightest thought of substituting laboratory instruction completely with simulation and online activities in chemistry is analogous to replacing all the experiences in the world with iPad applications, all books with a Kindle, and not to mention all the real people with virtual Avatars. There is a need of real experiences for real perceptual learning of chemistry by using the senses of sight, smell, touch and hearing.

Keeping some of these factors in mind, this dissertation research work focuses on the impact of laboratory instruction and its relevance for college level chemistry. Each chapter is different from the preceding chapter in terms of the purpose of the study and the research questions asked. However, the big idea is to address the importance of laboratory instruction in chemistry and its relevance in helping students to make connections with the chemistry content and in imparting skills to students such as problem solving, collaborative group work and critical thinking.

What follows is a brief introduction to the three different research studies on laboratory instruction pursued by this dissertation research. The first research study (Chapter 2) is about the impact of first year co-requisite general chemistry laboratory instruction as a on the problem-solving skills of students as compared to optional laboratory instruction. The second research study (Chapter 3) is about the impact of implementing student roles during the guided-inquiry based Science Writing Heuristic (SWH) approach. In the third research study (Chapter 4), critical thinking skills of first semester general chemistry laboratory students were compared to advanced (third or fourth year) chemistry laboratory students based on the analysis of their laboratory reports.

Introduction to the research studies and organization of the dissertation

Chapter Two of the dissertation studies is the impact of laboratory instruction on problem-solving skills of students in general chemistry. Overall, among educational institutions in the United States, the lecture and laboratory course are co-requisites for students enrolled in a first-year general chemistry course. However, there are some chemistry courses that do not have a co-requisite laboratory component. In such a case, students enroll only for the lecture component of general chemistry. In this chapter the emphasis of the research study is to understand some differences among students who take both the lecture and the laboratory course concurrently as compared to students who take only the lecture course for general chemistry. Does having a laboratory component make a difference to student learning in some aspect? In order to understand what effect the laboratory component of the course has on student learning, student attitude towards general chemistry, the logical thinking skills and problem solving abilities of students, both quantitative and qualitative data was collected for this mixed methods study. The second chapter opens with a thorough review of laboratory instruction, research on problem-solving in general and problem-solving specifically in stoichiometry and thermochemistry. The chapter continues with a brief discussion of the theoretical frameworks of Piaget's developmental learning theory and constructivism which guides the study. There is a section about research methods that includes an overview of the study, the research questions, and hypothesis, information about participants and the data collected, data analysis followed by results and discussion, conclusions, limitations of the study and further research.

Chapter Three of the dissertation describes the Student-Led Instructor-Facilitated Guided-Inquiry Laboratory approach (SLIFGIL). In this chapter the implementation of the Science Writing Heuristic (SWH) approach is extended further, with students leading the laboratory session in collaboration with their laboratory instructor. Students are assigned various roles that are consistent with the laboratory format for the SWH approach. Roles include beginning question expert, safety expert, procedure expert, data table expert, claims, evidence and analysis expert. This chapter opens with an abstract of the study and an introduction followed by the theoretical framework and literature review about laboratory instruction and the SWH approach. The other sections of the chapter include scope and intent of the study, research questions and hypothesis, experimental design, description of the modified SWH approach with details on the implementation of student roles followed by a section on data collection, data analysis, results and discussion, conclusions, the limitations of the study and the challenges. The end of Chapter Three leads into future research.

Chapter Four of this dissertation explores the impact of laboratory instruction on the critical thinking skills of students. This is a quantitative study in which student written reports were evaluated for critical thinking based on two different rubrics. The comparison groups in this study are students from freshmen level general chemistry courses Chemistry 167 laboratory for engineering majors, Chemistry 177 laboratory for science and engineering majors and advanced Chemistry 401 laboratory for chemistry and biochemistry majors. Students in Chemistry 177 laboratory were instructed using the SWH approach, students in

Chemistry 167 laboratory received traditional laboratory instruction, and students in Chemistry 401 laboratory also received traditional instruction. Chapter Four begins with an abstract and an introduction to the study on the impact of laboratory instruction on the critical thinking. The chapter continues with a literature review of the theoretical frameworks of constructivism, critical theory, writing to learn science, and the Science Writing Heuristic approach. The next section of the chapter outlines the purpose of the study followed by research hypothesis and research questions. There is a brief description of the three chemistry courses from which the student laboratory reports were collected, leading to an overview of the participants in the study, data collection and a summary of data analysis. The chapter continues to the results and discussions, conclusions, limitations of the study and concludes with some ideas on future research on the critical thinking skills of students at various levels in chemistry.

Chapters Two, Three and Four in the dissertation study portray the impact of laboratory instruction. The research study in chapter two on the comparison of student attitudes and problem solving in thermochemistry and stoichiometry is based on the concurrent enrollment of students in a chemistry laboratory course along with the lecture course. The study provides a snapshot of the impact of taking a laboratory along with lecture. Is there an impact of having a laboratory component along with the lecture or can students do as well in their study of first-year college chemistry without a laboratory component? The question is do laboratories make any difference in student attitudes and problem solving in the subject of chemistry?

Chapter Three is on the implementation of student roles in guided-inquiry based SWH laboratories. In a student-centered instructional approach all the students are expected to be active learners. However, in an environment where in the instructor is the sole facilitator of Science Writing Heuristic based laboratories, some students do not participate, come unprepared to do the laboratory activity and rely on their laboratory partners for data collection. Implementation of student roles was done to engage all the students and provide an opportunity to each student to be prepared for the laboratory and engage in learning from the laboratory activity by collaborating with peers and the instructor. Chapter Four examines the impact of guided-inquiry based instruction on critical thinking. A comparison is done based on evaluation of laboratory reports for two sets of students who are freshmen with upper classmen. The first group included students enrolled in an inquiry-based laboratory. The second group included students in the first year of a different chemistry laboratory course that is facilitated in a more traditional manner. The third group was the students who had at least three years of *traditional* laboratory instruction in chemistry.

Through this dissertation research there is strong evidence that laboratory instruction benefits students. An inquiry-based approach such as the Science Writing Heuristic can be implemented in ways that are more student-centered and provided students with opportunities to lead the laboratory activities each week and making them accountable for their learning. Inquiry-based instructional approaches may benefit students' thinking skills by providing them with the necessary scaffold to develop their critical-thinking skills when they make macroscopic observations during experimentation.

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CHAPTER 2

LABORATORY INSTRUCTION AND ITS IMPACT ON PROBLEM SOLVING IN GENERAL CHEMISTRY

Abstract

A number of studies have been done on the effectiveness of laboratory instruction. Some researchers have also questioned the relevance of laboratory work in freshmen level college chemistry. What happens when students enrolled in a chemistry course do not take an equivalent laboratory course? Does taking an integrated laboratory lecture course improve the problem solving skills of students in stoichiometry and thermochemistry? This study was conducted at a large public mid-western university in two general chemistry courses investigating student performance in the lecture, based on whether or not students enrolled in the laboratory. Students enrolled in the two different general chemistry courses were interviewed on four problems in stoichiometry and thermochemistry. Findings indicate that students concurrently enrolled in the laboratory and lecture had a better understanding of the concepts of stoichiometry and thermochemistry as compared to students who did not take a laboratory course along with the lecture.

Introduction

Laboratory instruction has an important place in the learning and teaching of chemistry. The term “Laboratory” has two dictionary meanings:

a) As a noun laboratory is defined as a workplace for the conduct of scientific research/ a building, part of a building, or other place equipped to conduct scientific experiments, tests, investigations, etc., or to manufacture chemicals, medicines, or the like.
b) A region resembling a laboratory in as much as it offers opportunities for observation and practice and experimentation /any place, situation, set of conditions, or the like, conducive to experimentation, investigation, observation, etc.

Likewise, the dictionary meaning of the term instruction is:

a) a direction; order;
b) The process or act of imparting knowledge/education.

The current scenario of laboratory instruction in a number of higher educational institutions can be identified as taking the first dictionary meanings for laboratory and instruction as defined above and summing it up as traditional instruction that is instructor-centered. In a traditional laboratory instruction, students have the facilities to conduct scientific research and to do investigations, but what they end up receiving is a direction or an order to verify the stated findings for an experiment using a recipe-based approach.

On the other hand, inquiry-based instruction is student-centered and provides students opportunities to observe, investigate, and experiment. The process/approach imparts knowledge and educates students about the concepts while engaging them to develop their reasoning, conceptual understanding, and problem-solving abilities simultaneously. Inquiry-based instruction fosters building an understanding of fundamental principles of chemistry and developing the concepts by proposing questions, making observations, collecting data, debating the findings, making knowledge claims, building evidence; negotiating an understanding with peers and the instructor, further refining the ideas, and comparing with established scientific principles. While traditional laboratory instruction emphasizes students' experimental skills, inquiry-based approaches promote thinking skills, learning of concepts in the context of laboratory activities, and are a great setting to address student misconceptions.

Another issue is that in many institutions of higher education, the laboratory and lecture course numbers are related, but this does not imply that students take both the lecture and the laboratory components of chemistry together in a given semester. A student may complete the laboratory first and then sign up for the lecture component of the course if laboratory is a prerequisite.

Research has shown inquiry-based laboratory instruction to be effective but there is not much evidence on what effect any kind of laboratory instruction has on students as compared to students receiving no laboratory instruction for a given chemistry course; neither have there been studies about students receiving laboratory instruction *before* the lecture component of chemistry or *after* the lecture component of a chemistry course in a different semester? What is the difference in students' academic performance when they take a chemistry course concurrently with the lecture component of the course?

The present study compares student's who take a laboratory course as a co-requisite to the lecture component to students who are not required to take a laboratory course along with the lecture in a given semester with regard to attitude, logical thinking skills, academic performance on hour exams, comprehensive final exams, and problem-solving in think-aloud clinical interviews about specific problems in stoichiometry and thermochemistry.

Literature Review on Laboratory Instruction

Why laboratory instruction?

Laboratory activities may be defined as “learning experiences in which students interact with materials or with secondary sources of data to observe and understand the natural world (Lunetta, Hofstein, and Clough, 2007). The role of laboratories in learning chemistry gained momentum in the early nineteenth century when scientists argued that learning chemistry requires extensive practice of chemistry with experimentation and reading (Foster, 1929).

Chemistry laboratories play an important role in student understanding of concepts by hands-on experience with underlying processes and direct observations, which cannot be accomplished by lecture or demonstration methods alone (Abraham et. al, 1997). Chemistry laboratory instruction may lead to the accomplishment of five general goals or learning outcomes as indicated in a survey study by Abraham et al (1997). These goals or learning outcomes include (a) concept development, (b) laboratory skills, (c) scientific processes, (d) positive attitude, and (e) learning factual information. As a result of the survey study, the development of concepts was considered to be the most important learning outcome by 199 institutions offering a first year general chemistry laboratory course.

In a review study on the role of laboratory instruction, Hofstein, and Lunetta (1982) emphasize the tremendous potential of laboratory instruction but they find prior research on the role of laboratory instruction on student learning and growth to be inconclusive. In another review study Nakleh, Polles, and Malina(2002), indicate a lack of evidence coming directly from students about their understanding based on laboratory experiences. They suggest further investigation of laboratory's potential in contribution to the development of metacognitive skills of students involved in the processes of problem solving, creative thinking, and scientific thinking. The review also places an emphasis on conducting research studies that have a blend of both qualitative and quantitative methods to further establish the relevance of laboratory instruction. Lazarowitz, and Tamir (1994) in their review study argued that students need concrete laboratory experiences involving data manipulation through the use of computers and a focus on the development of logical thinking and organizational skills.

Students' ability to answer a test question does not imply mastery of content (Spencer, 1999). It is important to understand whether students taking a laboratory course further apply the skills gained in the laboratory and connect to what they learn in the lecture and vice-versa. The difference between what students learn in a lecture setting and what they learn in the laboratory lies in their "first-hand experience of chemistry problems" whether in a traditional laboratory setting, and or in during concept exploration, invention and application (a.k.a. learning cycle) in a guided-inquiry based laboratory setting such as the Science Writing Heuristic (SWH) approach. In an SWH based approach, the students propose beginning questions and answer their questions by experimentation. For example, consider a weekly quiz problem in chemistry "What volume of 0.50 M aqueous sulfuric acid is required to neutralize a 25.00 mL 0.50 M aqueous sodium hydroxide solution?" A similar laboratory activity on acid-base titrations generally requires students to find the volume or molarity of an acid when added to a base of a given molarity and volume. Laboratory may be seen as a place to construct new knowledge instead of being viewed as a setting for the verification of factual information (Tobin, 1990; Spencer, 1999).

There is a very little evidence that traditional laboratory instruction does anything much except develop laboratory skills and factual information. Whereas, inquiry-based laboratories are used to explore, invent/ or introduce, and apply concepts and are inductive as students start with making observations and collecting data to generate concepts (Bates, 1978; Pavelich and Abraham 1979; Burke, Greenbowe and Hand, 2006).

While research reviews on the role of the effectiveness of laboratory instruction have silenced the critics who view laboratory work as not a significant contributing factor to learning of science (Toothacker, 1983; Hodson 1990, Kirschner and Meester, 1988); there is a need of further research to build more evidence on the implications of laboratory instruction for the learning of science.

Literature Review on Problem Solving

A problem exists when a person perceives a gap between where he or she is and where he or she wants to be but does not know how to cross the gap (Hays 1981). Problem solving is "what you do, when you don't know what to do." (Wheatley, 1984). Students generally misinterpret algorithms as problems. Algorithms are carefully developed procedures for getting right answers to exercises and routine tasks within problems with a minimum effort. It is an important ability for students, but markedly different from problems. Algorithms may constitute a step towards problem solving. Algorithmic questions may require problem solvers to follow a set of rules without any metacognition on the part of the student. There are three types of problems in general:

1. **Well-defined problems and ill-defined problems:** Well-defined problems have one solution and a limited number of solution paths; for example, what is the molar mass of

sodium chloride? Ill-defined problems may have a solution or solutions, but what information is needed and how to use that information is not straight-forward. Ill-defined problems may have many ways to address the problem, for example, what will future cars look like?

2. **Adversarial and non-adversarial problems:** In an adversarial problem, one person competes against other (as in games) and there is a winner and a loser. Non-adversarial problems are problems related to subject matter, and do not have a winner or a loser.

3. **Routine and non-routine problems:** End of chapter exercises may constitute routine problems as compared to real problems, which are non-routine and unfamiliar and require higher order thinking for solution.

Problem-solving abilities convey a lot about instructional approaches and how students transfer their understanding to new situations. Problem solving is what chemists do regardless of the area of chemistry in which they work. In addition, problem-solving skills are essential for individuals in order to be successful in their chemistry courses. "Individuals who have the capacity to address novel situations and can decide a suitable course of action are valued in society. Such a behavior is representative of problem solving." (Herron, 1996)

Wheatley defines problem solving as "*what you do when you don't know what to do?*"

The following steps may lead toward problem solving:

1. Try something.
2. Try something else.

3. Look at where the first two steps have taken you.

The strength of this problem-solving model (Wheatley, 1984) lies in the fact that it is linear with the techniques scientists use when doing basic research. General processes outlined by Herron (1996) for problem solving are:

1. **Understanding the problem:** involves understanding the goals of the task, the conditions placed on the problem, the unnecessary assumptions in the chemistry due to heavy vocabulary and ability to read and identify the errors for example, the terms such as *excess* in "*excess reagent*," treating in the phrase "*treating* the solid with". Treated and excess are common words that are used in everyday contexts but these have a different significance in the language of chemistry.

2. **Representation of the problem in terms of problem space:** how students represent the problem as an individual determines how and whether it will be solved. Problem space consists of the states of knowledge and operators that can be applied to elements in the space to produce new states of knowledge. Consider the problem: "On dissolving 3.000 g of an unknown metal chloride in water and then treating it with an excess of silver nitrate solution, 5.168 g of a precipitate of silver chloride is formed. What is the mass of the unknown metal?" While some students may view the above problem as a chemical reaction problem space, other students may perceive it as a mole problem space. The problem space has an influence on the way its solution is obtained. Thus, problem representation changes the course of its solution. The problem representation is also affected greatly depending on the level of the problem solver. If a student is an expert at

solving problem, his or her approach for representing the problem will significantly differ from that of a novice who operates on the face value of the problem.

3. The internal representation of the problem is followed by **execution of the plan for solution**. There is no single plan that can be applied over a variety of problems. A plan for problem solving requires conscious effort and reflection on the part of the learner, based on his/her conceptual framework and the level of expertise in the subject.
4. Students must **verify** their work to ascertain that the procedures applied and the conclusion reached are logically sound and correctly worked.

Clough (1997) suggests that intuition; creativity, imagination, serendipity, aesthetics, and logic all play a role in solving problems. There is no universal algorithmic method for solving problems. The conceptual framework of an individual determines problem solving, without which it would be difficult to define the problem in the first place. According to Gabel (1998), problem solving in any area is a complex process. It involves an understanding of the language in which the problem is stated, an interpretation of what information is given and what is sought, and an understanding of the concepts involved in the solution and in some cases, the ability to perform mathematical operations. **Students have difficulty solving chemistry problems that require mathematical skills**. Lack of success in solving problems discourages students from taking any chemistry courses after their first.

Solving chemistry problems requires students to possess conceptual knowledge, procedural knowledge, and the ability to translate the language of the problem to decode its meaning. The problem solver thus creates a cognitive structure according to the problem. Understanding the vocabulary of the problem is the first step towards successful problem, solving followed by demarcation of the relevant and the irrelevant data, identifying the variables involved, and the nature of the problem as to being an open ended solution or a multiple choice problem. (Gabel, and Bunce, 1994)

Herron, and Greenbowe (1986) have identified the following traits of a successful problem solver. Successful problem solvers:

1. Have a good command of the basic facts and principles.
2. Construct appropriate representations of problems.
3. Have general reasoning strategies that permit logical connections among elements of the problem.
4. Apply a number of verification strategies to ensure that:
    a. The representation of the problem is consistent with the facts given;
    b. The solution is logically bound;
    c. Computations are error free; and
    d. The problem solved is the problem presented.

Certain characteristics of unsuccessful problem solvers are impulsivity, lack of transfer of knowledge from one situation to another, breakdown in logical reasoning, inability to organize properly, and consider all relevant information in a problem solution and a misunderstanding of the problem goals. Unsuccessful problem solvers have gaps in their knowledge base and numerous misconceptions. They have fragmented knowledge in comparison to expert problem solvers and they often base their categorization of a problem on its surface features and not on the underlying concept (Bunce, 2005). Students' beliefs regarding the problem are reflected in the way they arrive at problem solutions. Students have the notion of chemistry as arbitrary and meaningless, with the questions emphasizing rote memorization and a recall of facts.

People involved in chemistry education have a view that problem solving leads to further conceptual understanding in chemistry. It indicates that students with a knowledge base in chemistry might solve conceptual problems better as compared to students who have little or no background information of the concepts associated with a particular problem. Researchers in the field of chemistry education have carried out numerous studies in this regard.

Nurrenbern, and Pickering (1987) carried out research studies at the freshmen chemistry level to find out whether the quantitative problem solving led to an understanding of molecular concepts among the students. They administered both the traditional problems and conceptual problems about gas laws and stoichiometry. The results of these studies revealed that students were more successful in solving traditional problems than conceptual problems. In the case of the gas law problems, two-thirds of the students in this study had no understanding of the critical attributes of gases such as the fact that gases occupy the entire volume of the container, though they could recall the fact of indefinite volume for gases. In the case of stoichiometry problems, the authors found that students did the problems algorithmically instead of displaying any understanding of chemical change at an atomic level. This study demonstrated that teaching problem solving to students differs from their conceptual understanding of nature of matter. The educational objective of problem solving does not necessarily lead to conceptual understanding and there are important differences between the two goals. However, if students get an exposure to experiences in the laboratory wherein they propose a hypothesis (problem), work as a group or in pairs to perform an experiment to answer their questions, make their observations, collect data, and answer their beginning questions, discuss, debate, and construct their conceptions, it may lead to a better understanding of the word problems they come across in a chemistry course. An effective laboratory instruction should be able to help students make connections between the concepts they learn in the lecture, the problems they solve with paper and pencil or online assignments to be a representation of phenomenon explored in the laboratory.

In a study by Gabel, Samuel, and Hunn (1987) on student understanding of the particulate nature of matter, it was found that students were able to use formulas in equations and balance equations correctly, without understanding the meaning of the formula in terms of the particles that the symbols represent. For example, in the equation $N_2 + 3H_2 \rightarrow 2NH_3$ students were unable to differentiate between $3H_2$ as ○○ ○○ ○○ and ○○○○○○. The poor understanding students had for these conceptual representations was attributed to a) a lack of formal operational development or poor ability to visualize, b) a lack of differentiation of concepts such as solids, liquids, gases, elements, compounds, mixtures, solutions, etc. and c) to the instructional shortcomings that fail to relate these terms to the particulate nature of the matter. Instruction with pictorial models at the molecular level aids students to construct scientifically correct conceptions in comparison to traditional instruction (Noh and Scharmann, 1997). Sawrey (1990) repeated the study of Nurrenbern and Pickering with a larger, more uniform group of students and separately studied student success on conceptual versus numerical problems for the top performers and bottom level performers in a class. To the authors' surprise; even high achieving students had difficulty with the concept questions. The best numerical problem solvers performed poorly on the conceptual questions.

In order to provide further evidence for the idea that the ability to solve a problem implies an understanding of the molecular concepts behind the problem (as indicated in the Nurrenbern and Pickering study), Pickering (1990) again replicated the study. The resulting argument of this replication study indicated student difficulty with conceptual questions was due to a knowledge gap and not due to some arcane difference in ability. Pickering concluded that problem solving, though a desirable ability, does not help much in the understanding of concepts at a molecular level and that ***"it is the understanding that is the heart of chemical science."*** The question is does laboratory instruction play any role in this understanding?

Further replication of the study on conceptual learning versus problem solving was carried out by Nakhleh, and Mitchell (1993). It was found that across all levels of chemistry students, from remedial to honors, conceptual problem solving ability lagged far behind algorithmic problem solving ability. Nakhleh, using paired exam questions, determined that a fairly sizeable percentage of the sample of freshmen (31%) were low conceptual/high algorithmic students. These students were skillful in solving algebraic equations, but displayed a limited understanding of the chemistry underlying the algorithmic manipulations. This indicates that having solved hundreds of calculation based problems, students have little faith in their conceptual abilities.

The problem solving behavior of students is difficult to observe and cannot be easily interpreted from problem solutions, (Eylon and Linn, 1988). Students are successful in defining concepts, but have a hard time representing their conceptual understanding.

One such study for evaluating student understanding of solution chemistry was carried out by Smith and Metz (1996) using microscopic representations of strong acids (HCl) and weak acids (HF). As a result of this study, the authors found that while many students could successfully define a strong acid as being completely ionizable, they could not relate this memorized information to the representations and incorrect representations. One particular student in this study recalled the formula for pH as $-\log[H^+]$ and could make out that a strong acid would have a pH of 1.0 so that $[H^+]$ is 10^{-1} but finds this information to be of no help beyond this. This indicated that algorithms can be used successfully without conceptual knowledge.

Students memorize definitions as facts without any conceptual understanding of the terms and the definitions. This lack of conceptual understanding shows up when students confront abstract concepts such as acids and bases that require students to use their visual ability and in such cases, an algorithmic approach may lead to nothing else but frustration among the students. Students have the notion that chemistry problems are generally math-based and can be quickly solved using formulas or equations from the textbooks. As stated by Bunce (2005):

> "The blind application of the rules without understanding how they work sets many students up for failure from the start. If students believe the main purpose of the word problems is to find a rule, plug in the numbers, and then enter the appropriate numbers in their calculator, they are less likely to be able to solve the Professor's challenging problems. Such students will also cheat themselves out of the opportunity to grow as successful problem solvers."

Research on problem solving in stoichiometry and thermochemistry

An understanding of the principles of stoichiometry has an important place in chemistry learning. Stoichiometry is a study of quantity of a substance involved in chemical reaction. It lays the foundation of understanding of the scale of reactions and demands proportional reasoning skills on the part of learners. In order to understand the stoichiometry of reactions and solve problems in the area, students need to have knowledge of atomic masses, chemical formulas of substances involved in a reaction, as well as an understanding of the law of conservation of mass. Research studies on stoichiometry have focused on problem-solving skills and/or strategies of students and how experts and novices differ in their problem-solving approaches on multiple choice or word problems in chemistry and on student misconceptions in stoichiometry (Yarroch, 1985; Atwater, and Alick, 1990; Gabel, Sherwood, and Enochs, 1984; Schmidt, 1990; Schmidt, 1992; Fach, de Boer, and Parchmann, 2007).

A vast number of students lack an understanding of the underlying concepts in stoichiometry. In their study on student problem solving in stoichiometry Huddle and Pillay (1996) found that on exam problems students display acute difficulties in their understanding of the mole concept. Students who could correctly identify the limiting reagent were able to solve the stoichiometry-based exam problems correctly. Similar findings were reported by Frazer, and Servant (1986) on solution stoichiometry problems in which only 21% of the students had a correct understanding of the underlying reaction stoichiometry while most of the students resorted to algorithmic approach to solve titration problems.

In a descriptive qualitative research study on problem solving strategies of high school students BouJaoude and Barakat (2003) found a moderate to high correlation between conceptual understanding and problem solving. They also reported better student performance on algorithmic problems as compared to the problems that required conceptual understanding of stoichiometry.

Thermochemistry is the study of heat energy changes that accompany chemical reactions. Because there is a wide range of the application of thermochemical reactions such as in metabolism, fuel-cells, combustion of fuels an understanding of thermochemistry is essential, especially for students pursuing science and engineering majors. Several studies have been done on student difficulties in understanding heat transfer (Cohen, and Ben-Zvi, 1992; Kesidou, and Duit, 1993; Johnstone, MacDonald, and Webb, 1977; Novick, and Nussbaum, 1978; Boo, 1998; Ben-Zvi, 1999; Thomas, and Schwenz, 1998; Barker, and Millar, 2000; Boo, and Watson, 2001). Researchers in these studies have reported frequent misconceptions among students in their understanding of heat and temperature; differences between endothermic and exothermic process; and energy changes accompanying bond breaking and bond formation processes.

Calorimetry is a technique used to measure heat exchange in physical and chemical processes. Very few studies though are, reported on the process of solution calorimetry or bomb calorimetry. Student performance on solution calorimetry problems were studied Greenbowe, and Meltzer (2003) in which a number of learning difficulties were revealed among students regarding the process of heat transfer in a dissolving process/ or a chemical reaction as a result of net increase and decrease in bond energies of the resultant solution.

Based on the literature review there is a lack of evidence on any connection between problem solving and student enrollment in a laboratory course. In addition, it is important to see whether enrollment in a laboratory course alters student attitude towards chemistry and impacts the problem-solving abilities of students.

Theoretical Framework

Early speculation in the of psychology of learning is credited to Immanuel Kant, a German philosopher, who was of the opinion that knowledge is acquired by people based on their sensory impression and a logical perception of things irrespective of experience.

Empiricism and nativism are two early theories about how people learn. According to the empiricist view, all knowledge is derived from sensory experiences. Thus, observation and feeling plays a great role in acquiring knowledge from the external world. Nativists such as Plato believed that knowledge already exists in the form of ideas and as one grows one is able to uncover these ideas. This view suggests the mind as the source of hidden knowledge, which surfaces with the maturity. Jean Piaget, a Swiss psychologist took this quest of knowledge acquisition further, by studying learning patterns of children and proposed the equilibration theory to explain the process. According to Piaget, the process of knowledge acquisition by individuals is explained in terms of processes such as intellectualism, apriorism, associationism, pragmatism and equilibrationism (Lawson, 1994).

Intellectualism describes the intellectual development of children who are equipped with an inner ability to construct knowledge by self-reflection of their actions. Such children use reason to contemplate their actions and their interpretation of reality is a thoughtful process. *Apriorism* implies ideas to be inherent in individuals and any experience or act as a means of verbalizing these ideas. *Associationism* implies that individual mental faculties develop because of acquisition of habits by direct contact or experience of the external world. The world is the source of all the knowledge. *Pragmatism* is related to the acquisition of knowledge based on behavioral changes. The existing knowledge of the individual is strengthened or abandoned in the light of behavioral successes. Thus, knowledge has an internal origin but is retained or abandoned based on interactions with the outer environment.

Equilibrationism is the process through which an individual attains harmony between self and the environment through assimilation and accommodation. Cognitive functions such as organization and adaptation remain constant throughout the development of the individual and cognitive structures or schemes such as assimilation and accommodation change both qualitatively and quantitatively with age and experience. Each person *assimilates* the world as he or she sees it. *Disequilibration* results when one finds it difficult to fit what one sees into his/her pre-existing mental schemes. *Equilibration* is restored by modifying the existing schemes and resolving the discrepancy to achieve the goals. The process of modifying the existing mental schema is *accommodation*. These four processes form the basis of constructivist theory in which the process of knowledge acquisition by an individual begins with input from the environment, as detected by the senses. The individual actively constructs knowledge from the data obtained by the senses and by further interaction of this data with an existing knowledge base (Jonassen, 1991; Von Glasersfeld, 1995). Besides developmental learning theory and the constructivist theory of Piaget, other theories such as social learning theory and behavioral theory also explain learning in individuals. According to the social learning theory, the cultural backgrounds, the language and the interactions of learners among themselves and with the experts influence learning (Vygotsky, 1929; Vygotsky, 1978). Behavioral theory explains learning as a change in the learners' behavior.

Constructivist theory has a great relevance for learning and teaching. Each learner is unique, and the way individual minds process knowledge also varies. Each person constructs his/her own knowledge subject to the condition that any knowledge constructed must fit reality, thus leading to a common knowledge across the group of people. Knowledge construction involves both building and the testing of a knowledge that is viable and workable (Bodner, 1986; Glynn, Yeanny, and Britton, 1991; Millar, 1989).

The *Learning Cycle* is the most familiar model for applying Piaget's ideas to teaching. Atkin, and Karplus introduced the idea of the Learning Cycle in 1962. The learning cycle has three stages. The first stage is the *exploration phase* in which students explore the phenomena containing the idea to be learned. Very little guidance is provided to the students during this phase as they explore new materials and new ideas. Activities for this stage are selected and planned in such a way that students encounter new phenomena, which they cannot explain or understand. The next stage is the *concept introduction phase*; students are introduced to the concept or the new idea they have explored in the phase one. The third phase of the learning cycle is the *application phase* in which the newly discovered or introduced concept is now put into practice by designing a set of activities which promotes application of the concept. The activities designed for learning cycle-based instruction should be developmentally appropriate for the intended student audience (Abraham, and Renner, 1986; Lawson, Abraham, and Renner, 1989).

Piaget has outlined four stages of intellectual development i.e. sensory-motor, pre-operational, concrete operational and formal operational. Students reach the formal operational about the age of twelve and reach the stage of complete intellectual development by the age of fifteen. The structure and the organization of concrete activities are directed towards objects or events that are concrete or present. Students at the concrete operational level have struggle thinking in terms of possibilities and find it difficult to understand concepts and principles that depart from reality (abstract ideas such as atoms, electrons, and nucleus). Scientific ideas are counterintuitive and cannot be acquired by merely observing phenomena (Clough, 2000). The formal operational student has the capacity to think in terms of possibilities and can reason out efficiently what might happen, without any visible aid. The student at concrete level can solve problems that require formal thinking, provided the students gets an opportunity to deal with the formal concept using some type of concrete experience that can lead to real observations as a special case of the possible (Herron, 1975). Thus, the starting point of formal thinking is often in terms of concrete when encountering anything unfamiliar. Laboratory activities provide a unique opportunity for students to develop their formal thinking skills.

The key difference between formal operational thinking and concrete operational thinking is that if, the concrete operational thinking with the same logical operations is applied while dealing with abstract concepts, it would be considered a characteristic of formal operational thinking. According to Herron (1975), "Formal operational thinkers display qualities of thinking in terms of possibilities, consider all possibilities in a given situation, and are able to recognize logical necessity given all other things being equal. The formal operational students can control the variables before drawing any conclusions about the effect of some manipulated variable."

Formal thought is characterized by the ability to imagine unobservable entities. It is not context bound. A formal thinker can read a written description of an ion in solution and form a mental model of the solution (Cracolice, 2005). Herron has tabulated competencies commonly expected of general chemistry students, which cannot be understood by students who are not formal operational thinkers. However, these are hypothesized differences and based on the author's judgment of the mental activity required to accomplish the task. The question is whether taking a laboratory course concurrently with lecture in general chemistry or the lack of a laboratory experience concurrently with lecture leads to different formal operational competencies among the students in the two groups.

The competencies commonly expected of general chemistry students at formal operational and non-formal operational level as outlined by Herron (1975) are presented in Table 1.

From the list of tasks generated by Herron (1975), it can be said that formal thinkers have some expertise of the subject and display an advanced level of comprehension of chemical concepts as compared to concrete operational thinkers. While the concrete operational thinkers can think only in terms of real and possible, formal thinkers are a step ahead and can think in terms of possibilities or abstractions. In addition, concrete experiences in laboratory can further reinforce concepts and lead students to thinking about possibilities by exploration of scientific concepts in a laboratory.

The instructor has to vary his/her teaching strategies considering the fact that knowledge cannot be transferred intact from his/her mind to the pupils' minds by lecturing or reading a text. Providing information to students on a massive scale does not by itself, necessarily lead to learning. The complexities of human cognition cannot be classified into a simple category, just as chemical bonds cannot be classified as purely ionic, covalent or metallic.

Table 1: Competencies commonly expected of general chemistry students.

	Students who have not reached formal operational thinking CAN	Students who have not reached formal operational thinking CANNOT
1	Do any routine measurement or observation.	Do measurement of density, heat of reaction and other "derived" quantities which are not observed directly.
2	Make inferences, which are direct extrapolations from the observations, e.g., "wood objects burn" as an inference following the observation of several wooden objects which burn.	Make inferences which are "twice removed" from observations, e.g. "the paper, the wood the gasoline all burned; these are carbon compounds; carbon compounds burn.
3	Comprehend the idea that the ratio of the mass (or volume) of hydrogen to the mass of oxygen in the water is constant. (This should be in the "can do" list only if the idea is developed from the actual observation of data or through a procedure which enables the student to understand the source of the data.)	Reason that the constancy of mass ratios and volume ratios in substances such as water leads us to a conclusion that compounds can be represented as particles made up of atoms combined in definite proportions.
4	Construct cooling curves for pure and impure substances and infer from the shape of the cooling curve of an unknown substance whether the unknown is pure (or a eutectic mixture) or impure.	Explain why a plateau occurs in the cooling curve of a pure substance during a phase change.
5	From a description of the behavior of a gas using a physical model (such as the Molecular Dynamics Simulator); predict the effects of increasing temperature on the average kinetic energy and distribution of energies among molecules of a gas.	From the postulates of kinetic theory, predict those conditions of temperature and pressure under which real gases will not obey the ideal gas law.
6	From the definition of molarity, prepare 1000 mL of a 1 M solution.	From the definition, prepare 25mL of a 2.5 M solution. Prepare 1000 mL of 0.25 M solution from a 3 M stock solution.
7	Follow a set of rules to find the empirical formula of a compound.	Understand why following the rules will result in the empirical formula.
8	Conceive of atomic weight as the mass of a given number of atoms, i.e., the atomic weight is the weight (mass) of $6.02 x 10^{23}$ atoms.	Conceive of an atomic weight as the ratio of the mass of some atoms to the mass of some other atom which is selected as a standard.
9	Use the factor-label method to solve problems in instances where the units provide an indication of the operation to be performed.	Use ratio and proportion to solve problems which will not fit into a "type" problem which has been memorized.
10	Balance equations, write formulas, calculate molecular weight etc. using set rules.	Derive the rules for balancing equations, writing formulas etc. from general principles such as the law of conservation of mass or the law of definite proportions.
11	Conceive of acid as any substance that will turn litmus red.	Conceive of an acid as a proton donor or an electron pair acceptor.
12	Demonstrate that a solution contains ions by showing electrical conductivity; measure the current flowing in a solution; show that the mass of metal deposited on an electrode increases regularly with the current or with time.	Predict changes in time that would be needed to compensate for an observed change in current, use the amount of current and the time to calculate the number of atoms of metal deposited.
13	Apply rules concerning reaction rates to predict changes in rate that would result from changes in the temperature and concentration.	Explain the effect of temperature change or concentration change in terms of collision theory.
14	Observe the effect of a change in temperature, concentration, or pressure on the concentration of some component of a system originally at equilibrium and predict the nature of the system when additional changes of the same type are made.	Predict the effect on some other component of the system when the same changes in pressure, temperature or concentration are made.
15	Knowing the volume of base needed to neutralize 1 g of acid, calculate the volume of base needed to neutralize any amount of acid.	Knowing the concentration of base and the volume needed to neutralize a given volume of acid, calculate the concentration of acid.
16	Place various metals into a solution containing a metal ion and use the data to place the metals above or below the metal in solution (begin constructing an activity series).	Use data from a series of experiments such as this where some metals appear only in ion form where the others appear as metals to construct an activity series.

However the constructivist theory of knowledge acquisition applies broadly over the chemistry curriculum: people construct meaningful scientific knowledge for themselves based on their experiences (Cracolice, 2005). The constructivist approach offers an invaluable insight in emphasizing that the learner in the learning process necessarily reconstructs any knowledge. The constructivist model plays a role of involving the students in learning a pre-determined body of agreed knowledge (i.e. consensually agreed scientific theories rather than personal theories about phenomena).

The constructivist model is also helpful in explaining misconceptions that students bring to chemistry and the resistance of these misconceptions to any change by instruction. For example, a majority of students believe that bubbles of boiling water are made up of heat, air, oxygen, or hydrogen. Many children also believe that nothing remains when a gas is burned; only taste remains because of dissolving sugar and only smell travels across the room on heating camphor and there is loss in mass of iron nails due to rusting (Osborne and Cosgrave, 1983). Bodner defines the difference between preconception and misconception as:

> "A preconception is a concept or an idea which a student has upon entering a course, and which has some consequence on the persons' work. The term misconception is used for ideas or concepts which, from the viewpoint of an average professional, lead to unacceptable solutions or answers to questions or problems in the context of a course."

One way to replace students' misconceptions is by constructing a new concept, which more appropriately explains their experiences thus leading to meaningful learning. This suggestion of Bodner (1986) is analogous to Kuhn's argument that "one cannot get rid of an old theory by proving it wrong through experimentation as the proponents of theory will make ad hoc modifications explaining the new experimental results. Best way to prove a theory wrong is by proposing a new theory that does a better job at explaining the experimental evidence." Similarly, students having misconceptions will align their understanding to defend their misconceptions unless, as a learner, they choose to accommodate the new conceptions and discard the old misconception based on experience by altering their existing mental schema(s).

According to Novak (1998), the pre-requisites of meaningful learning are: (a) relevant prior knowledge on the part of the learner that relates new information to be learned in some non-trivial way; (b) meaningful material, that is the new knowledge is relevant to some other knowledge and contains significant concepts and prepositions; (c) the desire and willingness of the learner to learn meaningfully through conscious deliberation, relating the new information to the existing knowledge in a non-trivial way. Highly meaningful learning includes problem solving and creativity and is possible in those knowledge domains in which the learner has a considerable well-organized prior knowledge (Novak, 1998).

Herron (1996) explains that learning differs from student to student and depends on the path each student takes to learn. The learning process is influenced by many variables such as the characteristics of the learner, what is to be learned, what the learner does to learn, and what is taken as evidence that learning has taken place. It is difficult to measure intelligence as it differs from person to person and is, to some extent, a biological trait (genetics). Everybody processes external information differently, however there is no evidence suggesting that normal people lack the equipment to learn science. Knowledge construction occurs in our minds under the control of schemas that were either present during the time of birth or constructed later through assimilation and accommodation. Key ideas of constructivism and cognitive theories of learning are summarized in Table 2:

Table 2: Constructivism and cognitive theories of learning.

Constructivism	Cognitive Theories (Discovery learning-Bruner; Cognitive Development-Piaget)
Knowledge is constructed with individual actions or social influences.	Changes in mental structures that contain information and procedures for operating on that information.
Learner constructs his/her own sets of meanings (psychological constructivism) or by means of language (social constructivism).	Learner constructs knowledge and is actively seeking meaning.
Learning is enhanced by providing activity- based instruction and promoting learning in collaborative groups.	Interacting with the physical world is crucial. What the learner brings to the learning environment and developmental differences in reasoning affect science learning.

Motivation and Purpose

The motivation for this study comes from the observation of students in two different general chemistry courses Chemistry 167 and Chemistry 177. Chemistry 177 is mainly pursued by science majors and Chemistry 167 primarily consists of engineering majors. In many non-formal discussions with colleagues in chemical education, the engineering major students were often referred to as students who were more interested in numbers. A reason that led to this study was the fact that not all the students who enroll for Chemistry 167 lecture course take the Chemistry 167 laboratory course concurrently. In the case of Chemistry 177, students who sign up for the lecture component of the course are required to enroll in the Chemistry 177 laboratory concurrently and complete both the lecture and the laboratory component in the same semester. The purpose of this study is to understand the impact of concurrent lecture and laboratory instruction in general chemistry on a student's problem solving ability. In order to assess whether the laboratory instruction is leading to any learning of chemistry concepts and principles students' performance was compared on specific think-aloud interviews for problems on stoichiometry and thermochemistry for the first year of general chemistry.

Research Hypothesis and Research Question(s)

In this study it is hypothesized that concurrent laboratory instruction plays an important role in student problem solving. Students enrolled in a laboratory chemistry course along with the lecture component in general chemistry have better attitudes and logical thinking skills as compared to students who take only the lecture course in general chemistry. It is also hypothesized that students who take a laboratory course in the same semester in which they pursue the lecture component of the course, have a better understanding of the concepts and are thus are adept in solving simple as well as complex problems in stoichiometry and thermochemistry. The research study was guided by the following research questions given the theoretical framework and the literature review on laboratory instruction and problem solving as previously outlined.

1. Do the students enrolled in a laboratory course along with the lecture perform academically better than students NOT enrolled in a laboratory course along with the lecture?
2. Are there any differences in a) student attitudes and b) logical thinking skills among students who take a laboratory chemistry course along with the lecture component of the course when compared to students who only take the lecture component of the general chemistry course?
3. Are the students enrolled in both lecture and laboratory courses for general chemistry better problem solvers in thermochemistry and stoichiometry than students enrolled only in lecture portion (with optional lab component)?

Research Methods

This is a mixed methods research study on student problem solving skills on specific problems on the topics of stoichiometry and thermochemistry (Towns, 2008; Creswell, and Clark, 2011). The work incorporates students' academic performance on written exams and an extensive interview data from a subset of students who were (a) enrolled in both the lecture and laboratory course and (b) students enrolled only in a lecture course during a semester.

Participants

The study was conducted for two separate lecture and laboratory courses in general chemistry: Chemistry 167 and Chemistry 167L (for engineering majors) and Chemistry 177 and Chemistry 177L (for science and chemical engineering majors). As indicated earlier the purpose of this study is to determine the impact of concurrent laboratory and lecture instruction on student academic performance and problem solving for specific topics in general chemistry.

For the Chemistry 177 lecture and 177 laboratory course 919 students consented to participate in the research study. In the case of the Chemistry 167 lecture and laboratory course 710 students consented to participate. Out of all who participated in the study the study focused on students who enrolled with laboratory course and lecture courses concurrently for Chemistry 177. In case of Chemistry 167, the focus was on subjects who were (a) enrolled in the lecture and laboratory components during the same semester, or (b) who were only enrolled in the lecture component. All the subjects in the study (N=362) for first semester general chemistry course were concurrently enrolled in the Chemistry 177L laboratory course and Chemistry 177 lecture course. In the case of the accelerated general chemistry course for engineering majors, the majority of students in this study were enrolled in the Chemistry 167 lecture component (N=253), whereas less than half of these students (N=106) were enrolled in both the lecture and the laboratory component of the course concurrently.

The majority of students were first year college students in the age group of 18-20 years. Students in Chemistry 177 and Chemistry177L were majors in science and some areas of engineering such as material science, chemical engineering, and construction engineering and so forth. The students in Chemistry 167 and 167L were primarily engineering majors. The subjects in the study were present for 90% or more of the course assignments and completed all the lecture examinations and the comprehensive final examination.

Course and Instruction

General Chemistry 167 is a one semester accelerated course designed for students with an excellent preparation in math and science. It is a terminal course for engineering students who do not plan to take additional courses in chemistry. The lecture component of Chemistry 167 was taught by two instructors with three lectures per week conducted by the first instructor and two lectures per week by the second instructor but with an almost similar time distribution on each topic. Both instructors covered similar material though their pace was slightly different.

Chemistry 167L is a laboratory course for engineering students. The laboratory course requires the students to have concurrent credits for Chemistry 167 or the students must have completed Chemistry 167 credits to be eligible for Chemistry 167 laboratory. A third instructor was in charge of the Chemistry 167 laboratory course and multiple TAs served as laboratory instructors who reported to the supervising professor. The Chemistry 167 laboratories meet once every week during the semester. A laboratory section for Chemistry 167 may have had one to two teaching assistants at a time. The number of teaching assistants in a given laboratory depended on the room capacity. A larger laboratory room could hold up to maximum 40 students and had two teaching assistants. The smaller laboratories held a maximum of 20 students and had one teaching assistant. The general ratio in these laboratories was approximately 18 students to one teaching assistant in a given section. The laboratory manual used for Chemistry 167 had thirty experiments out of which students performed thirteen during the semester. All the students enrolled in the laboratory for this study also took the lecture course concurrently.

The students in the lecture component of Chemistry 167 took four hour exams and a final exam. The students in the laboratory component of Chemistry 167L had four laboratory practical tasks related to the laboratory activities during the semester.

Science and engineering majors enrolled in general Chemistry 177 accompanied by the Chemistry 177L course. Students enrolled in the lecture component were required to enroll for the laboratory component of the course. Chemistry 177 is the first semester course of a two semester sequence which explores chemistry at a greater depth. The emphasis of chemistry177 is on concepts, problems, and calculations. The course is mainly designed for physical and biological science majors, chemical engineering majors, and all others intending to take 300-level chemistry courses. Three instructors taught the lecture component of Chemistry 177 with three lecture sessions per week. The course was covered at the same pace and similar content was covered in all the three sections. The hour exams, quizzes and assignments were similar for all three sections of Chemistry 177. The laboratory component of the course was conducted by the teaching assistants under the supervision of the professor in charge of the laboratory course who also taught a section of the Chemistry 177 lecture course. There was one teaching assistant per laboratory section with a student to TA ratio of approximately 18:1. The laboratory experiments and lectures were closely coordinated. Depending on the pace, a topic was first covered in the laboratory and then in depth during the lecture or vice-versa. Students conducted fourteen experiments out of a possible fifteen experiments from the laboratory manual which was based on a guided-inquiry based Science Writing Heuristic approach. The Chemistry 177 laboratory involved the use of an inquiry format of teaching, while the laboratory instruction for Chemistry 167 course involved a traditional-verification approach.

Data Collection

Data collection was done in view of the mixed methods research design. Both the quantitative and the qualitative data was collected concurrently and analyzed simultaneously. For the purpose of baseline comparison of all students enrolled in the Chemistry 177, Chemistry 177 laboratories, Chemistry 167, and Chemistry 167 laboratories, an online version of departmental Chemistry Placement Test was administered to the students four weeks prior to the semester. The Chemistry Placement Test was used to assess students' prior chemistry knowledge and to assist academic advisors and students in selecting an appropriate chemistry course. For this research study, the placement scores were used to determine whether there were any initial differences between the knowledge and skills of students in the lecture and laboratory components of Chemistry 167 and Chemistry 177.

For determining any change in attitude towards chemistry among the students in a lecture-laboratory course as compared to students in only a lecture component of the course, a version of a Bauer's Attitude toward the Subject of Chemistry Inventory (ASCI.v2) was used (Bauer, 2005; Bauer 2008) The ASCI.v2 is a shortened form of the actual instrument and it contains only two factors from the original instrument. The factors in ASCI.v2 were used to measure students' emotional and intellectual attitude towards chemistry (Lewis, Shaw,and Heitz, 2009; Brandriet, Xu, Bretz, and Lewis, 2011). The shortened version of the instruments took less than two minutes for the students to complete and was used as a pre-measure and post-measure of attitude of students enrolled in Chemistry 167 lecture only, in Chemistry 167 lecture and laboratory both, and in Chemistry 177 lecture and laboratory both. The instrument thus served as a pre- and post-test for measuring the attitudes towards general chemistry of the study participants. In ASCI.v2, students answer eight questions. Four out of these eight questions measure the *Intellectual Accessibility* and four questions measure *Emotional Satisfaction* among students for their attitude towards the subject of chemistry. The adjectives hard/ easy, complicated/ simple, confusing/ clear and challenging/unchallenging measure *Intellectual Accessibility* and *Emotional Satisfaction* is measured by student responses for using adjectives uncomfortable/ comfortable, frustrating/ satisfying, unpleasant/ pleasant and chaotic/ organized. In Bauer's shortened version, students circle a number from 1 through 7 on these polar adjectives that measure the two attitudinal factors.

In order to compare the logical thinking skills of students among the laboratory and lecture and lecture only groups, a Test of Logical Thinking (TOLT) was administered to students towards the end of the semester. The TOLT was developed by Tobin and Capie (1981). The TOLT is a 10-item written test that was designed to assess cognitive development with respect to specific Piagetian tasks. The TOLT contains two items for measuring each of the five formal reasoning modes namely (a) proportional reasoning, (b) controlling variables, (c) probabilistic reasoning, (d) correlational reasoning, and (e) combinatorial reasoning (Tobin, and Cape 1981; Triflone, 1987); Ahlawat, and Billeh, 1987).

For comparing student academic performance, copies of the hour exams were made. Student scores on the hour exams and their final exams scores were used to assess their progress during the semester. Hour exams have two parts; part 1 is multiple choice and part 2 of the test is in worksheet format. Each hour exam is scored out of total 100 points for both the Chemistry 167 and Chemistry 177 courses. Students take four hour exams and a comprehensive final exam for both general Chemistry 167 and Chemistry 177. Students in Chemistry 177 partly took the first semester American Chemical Society's General Chemistry Test and the department exam combined as their final comprehensive exam which has a multiple choice format. Students answered 40 questions in the first semester ACS general chemistry test and 25 questions for the department exam both of which were scored out of a maximum of 150 points. Students in Chemistry 167 took a comprehensive final exam consisting of 64 questions generated by the instructor. This format was multiple-choice and was scored out of 200 points maximum.

In order to compare problem-solving skills of students on the topics of stoichiometry and thermochemistry student interviews were conducted. Students enrolled in Chemistry 167, Chemistry 167L, Chemistry 177 and Chemistry 177L were invited to participate in think-aloud interviews via announcements made by the teaching assistants. Students who consented to participate in the study were further contacted via emails. Overall forty students were interviewed; twenty students were concurrently enrolled in Chemistry 177L. Twenty students were enrolled in Chemistry 167 out of whom, eighteen students were enrolled in only Chemistry 167 and were not taking any laboratory course concurrently. These students have had some laboratory experience during their high school chemistry. Only two students out of twenty that were interviewed from Chemistry 167 were enrolled concurrently in the Chemistry 167L. This leads to two groups of students that were interviewed-students who have a concurrent laboratory course along with the chemistry lecture course (N=22) and students who are only enrolled in a chemistry lecture course (N=18) during their first semester of general chemistry at the college level.

The think-aloud interviews were semi-structured. Students were asked questions about their background in chemistry and were probed on their problem solving on stoichiometry and thermochemistry-based problems. In order to capture student response as completely as possible, interviews were video-taped using two cameras that were directed at the participants and a digital voice recorder was used to capture dialog. Students were provided with problems on stoichiometry and thermochemistry on a worksheet. In addition periodic tables, calculators, textbooks, and internet enabled computers were provided to participants in case they needed any reference to work on chemistry problems during the think-aloud interviews.

Data Analysis

Quantitative data was first entered in an Excel spreadsheet and then transferred to the JMP 9.0 statistical program to generate distributions for the students in various chemistry courses. Statistical tests of significance such as the independent samples t-tests and matched pair t-tests were performed to compare the students in a concurrent laboratory course and students enrolled in only the lecture component of a general chemistry course. Student interview worksheets were scanned, coded for anonymity, graded, and compared for difference on scores in problem solving. A grading rubric was developed based on the responses of the instructors teaching Chemistry 167 and Chemistry 177 lectures on the interview worksheet problem. Three instructors were interviewed on similar problems for stoichiometry and thermochemistry for generating a rubric. The interview worksheet solutions of students were scored based on the rubric and were quantitatively compared using non-parametric Wilcoxon Test due to a small sample size for students enrolled in laboratory versus students not enrolled in the laboratory along with the lecture portion of general chemistry.

The qualitative interview data was analyzed in order to supplement findings from the quantitative data. Audio and video files of student interviews were transcribed in full in a text file using MS word and transferred to the ATLAS.ti qualitative package for developing codes and data analysis. Student interview notes were also entered in a word file and transferred to ATLAS.ti for generating additional memos and assigning codes. Codes were further used to determine any patterns in problem-solving among the students in laboratory plus lecture versus the lecture-only group.

Results and Discussion

Distributions Chemistry 167 and 167L

The distribution for study participants is given in Table 3. In this study the number of males is higher in each of the three groups 167, 167/167L and 177/177L. Comparison of mean score between males and females was not done due to the fact that number of females from Chemistry 167 and Chemistry 167L who participated in this is relatively too small to determine any significant differences.

Table 3: Gender distribution for chemistry 167, 167/167L and 177/177L students.

Gender	General Chemistry 167	General chemistry 167 and 167 L	General Chemistry 177 and General Chemistry 177L
Male	224	98	205
Female	29	8	157
Total	253	106	362

For a baseline comparison of the students in Chemistry 167, students in Chemistry 167 lecture and laboratory, and students in Chemistry 177 lecture and laboratory, departmental chemistry placement test scores were used. The mean score gives an idea of the centrality of the data. The standard deviation gives an idea of the distance of the observations from the mean value and is often used to compare several distributions for their spread or distance from the mean values. The mean chemistry placement scores and the standard deviations for the students in the three groups 167, 167/167L and 177/177L are fairly close as seen in Table 4.

Table 4: Chemistry placement test - Average score, standard deviations and confidence intervals.

Level	Number	Mean	Std Dev	Lower 95%	Upper 95%
167	253	34.27	8.24	33.25	35.29
167/167L	106	33.06	8.37	31.45	34.67
177/177L	362	34.68	8.22	33.83	35.53

A one-way ANOVA test at α=0.05was performed to determine whether there were any significant differences among the three groups at the beginning of the semester (Table 2). The ANOVA (Analysis of variance) is a parametric approach which is used to test hypothesis about the means. An ANOVA calculates the ratio of two variances for the means. The ratio of variances between and within-groups follows an F-distribution (Hamilton, 1996). At the beginning of the study, analysis of variance showed no statistical significant difference between the students in laboratory and students in lecture and laboratory, $F(2, 718)=1.57$, p-=0.20,

Table 5: One-way ANOVA for chemistry placement mean scores.

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Group	2	214.503[a]	107.251	1.5744	0.2079
Error	718	48913.186	68.124		
C. Total	720	49127.689			

[a] R-squared=.004 (Adjusted R Squared=.001).

The mean scores of students of students in the two general chemistry courses Chemistry 167 and Chemistry 177 were not compared for the difference in mean scores as the students in these two groups were tested for content that was covered at a different pace. Overall it is possible to draw general trends for each of these two courses independent of one another for exam scores as students in both these courses take the departmental Chemistry Placement Test; have four hour exams and a final exam during the semester.

The first research question concerns the comparison of the academic performance of the students who take a concurrent laboratory course along with the lecture. The mean and standard deviations for students in the three groups (Chemistry 177/177L; Chemistry 167/167L, and Chemistry 177) are summarized in Table 6, Table 7, and Table 8. As can be seen from Table 6, in the case of students from 177/177L there is a slight decrease of mean from for Exam II and Exam IV, yet overall the students maintain an average score as being greater than 70% for the four hour exams and the comprehensive final exam.

Table 6: mean(s) scores for exams with standard deviation (s) for students enrolled in Chemistry 177 and Chemistry 177L concurrently.

Exam(s)	Mean	Standard Deviation
Hour Exam I (100 points)	76.88	12.58
Hour Exam II (100 points)	73.17	17.11
Hour Exam III (100 points)	79.54	11.96
Hour Exam IV (100 points)	78.26	12.69
ACS Final+ Department Exam (150 points)	70.94	13.14

The students who took a laboratory course along with the lecture course for Chemistry 167 show a decline on the mean scores for their fourth hour exam and a sudden sharp increase for the comprehensive final exam as seen from the mean scores in Table 7. A trend that can be seen as common for both the Chemistry 177 and 177L group and Chemistry 167 and 167L is the drop in the mean score for Exam II. One possible explanation of this trend could be the shift in the content that requires simple reasoning towards more complex thinking. In Chemistry 177, the first hour exam tested basic skills that require conversion factors, use of dimensional analysis, and an introduction to atoms, molecules, ions and nomenclature of simple compounds. By the second exam, students in Chemistry 177 learn about the stoichiometry of chemical reactions and solution stoichiometry. Students in Chemistry 177 thus move from simple logical processes as 1 dozen=12 units to chemical reactions such as “if 1x react with 3y to form 4z, how many x would be required to form 7.5z?” Such problems require proportional reasoning about reactions at the microscopic scale during lecture-based instruction. Similar problems are presented through experiments to students on a macroscopic scale through hands-on experiences in the guided-inquiry based laboratories.

In the case of Chemistry 167 and Chemistry 167L concurrently enrolled students and students enrolled in only the lecture component of Chemistry 167 there, is a similar trend for hour Exam II and hour Exam IV. There is a greater drop in the mean score in the case of students of Chemistry 167/167 L and Chemistry 167 students. The content undergoes a shift from the basic understanding of measurements and mole ratios for exam I to topics of electronic structure of atoms, stoichiometry and gas laws for Exam II.

Table 7: Mean(s) and standard deviation(s) of students enrolled in Chemistry 167 and Chemistry 167L concurrently.

Exam(s)	Mean	Standard Deviation
Hour Exam I (100 points)	79.71	11.18
Hour Exam II (100 points)	70.74	14.34
Hour Exam III (100 points)	74.77	12.28
Hour Exam IV (100 points)	59.41	15.19
Final Exam (200 points)	78.56	10.84

Table 8: Mean(s) and standard deviation(s) of students enrolled in Chemistry 167 lecture component only.

Exam(s)	Mean	Standard Deviation
Hour Exam I	77.15	13.90
Hour Exam II	67.78	15.33
Hour Exam III	72.34	13.37
Hour Exam IV	57.50	19.41
Final Exam	76.01	12.48

In order to determine whether taking a laboratory course along with the lecture for general chemistry impacts student performance, the mean scores on hour exams and the comprehensive final exam of students concurrently enrolled in Chemistry 167 and Chemistry 167L were compared for statistical significance with the score for the students enrolled only in the lecture component of Chemistry 167. Sample variances were assumed to be unequal due to difference in the sample size for the two groups. The mean score of students concurrent enrolled in the laboratory as well as the lecture course are higher than scores of students enrolled only in lecture. A one-tailed t-test at α=0.05 showed the mean of the students in the concurrently enrolled Chemistry 167/ Chemistry 167L to be significantly higher for hour Exam I, hour Exam II, hour Exam III and for the comprehensive final exam.

Table 9: Two-sample t-test comparison of chemistry 167/167L and Chemistry 167 students.

	167/167L (N=106)		167 (N=253)		T-test				
Hour Exam	Mean	SD	Mean	SD	t-ratio	Prob>t	D.F.	Cohen's d	Effect Size
I	79.17	11.18	77.15	13.90	1.84	.033*	242.52	0.160	0.079
II	70.74	14.34	67.78	15.33	1.74	0.040*	209.49	0.199	0.099
III	74.77	12.28	72.33	13.37	1.66	0.048*	213.18	0.197	0.098
IV	59.41	15.19	57.49	19.40	1.00	0.158	249.06	0.110	0.055
Final Exam	78.56	10.83	76.00	12.48	1.93	0.026*	225.22	0.217	0.108

Bauer pre- and post-Test ASCI.v2 (Appendix A)

A matched pair t-test was performed for student responses on Bauer's ASCI.v2 pre- and post-test survey. Student responses were compared across all three groups for any patterns in attitudinal differences between the laboratory and non-laboratory students in the two chemistry courses, Chemistry 167 and Chemistry 177.

As mentioned before, Bauer's Attitude toward the Subject of Chemistry (ASCI) test was developed to measure a student's self-concept as a chemistry learner. In order to measure student attitude towards the subject of chemistry, Bauer developed a semantic differential inventory (Bauer, 2008; Brandriet, Xu, Bretz, and Lewis, 2011). A shortened version of Bauer's test was pilot tested by Xu, and Lewis (2010) which is the ASCI version 2. The shortened version of Bauer's test measures student attitudes towards the subject of chemistry by emphasizing the two factors of *Intellectual Accessibility* and *Emotional Satisfaction*. The shortened two-minute version was easier to use in a large setting like Chemistry 167 and 167L and Chemistry 177 and 177L in which students enrollments are close to a thousand.

CHEMISTRY IS			
1	easy	|__1__|__2__|__3__|__4__|__5__|__6__|__7__|	hard
		middle	
2	complicated	|__1__|__2__|__3__|__4__|__5__|__6__|__7__|	simple
3	confusing	|__1__|__2__|__3__|__4__|__5__|__6__|__7__|	clear
4	comfortable	|__1__|__2__|__3__|__4__|__5__|__6__|__7__|	uncomfortable
5	satisfying	|__1__|__2__|__3__|__4__|__5__|__6__|__7__|	frustrating
6	challenging	|__1__|__2__|__3__|__4__|__5__|__6__|__7__|	not challenging
7	pleasant	|__1__|__2__|__3__|__4__|__5__|__6__|__7__|	unpleasant
		middle	
8	chaotic	|__1__|__2__|__3__|__4__|__5__|__6__|__7__|	organized

Figure 1: Bauer ASCI.v2

Students answered a pair of eight polar objectives that measured their emotional satisfaction with chemistry and the intellectual accessibility of the subject for them. Students rated these adjectives from number 1 to number 7 on how well the opposing words describe their feelings towards chemistry. A summary of matched pairs Bauer's pre-and post-test is given in Table 10 for students enrolled only in the lecture component of Chemistry 167. As seen from the summary statistics, students in Chemistry 167 find chemistry easy to begin with but rate it as hard towards the end of the semester with statistically significant differences ($t=4.09$, $df=252$; $p=.0001$*) in the pre- and post test of their attitudes. Overall, students who took only the lecture component showed significant differences in their attitudes on the pre-and post-test on intellectual accessibility of chemistry as they find Chemistry to be statistically significantly easy, simple, clear and unchallenging at the beginning of the semester. Students enrolled in the lecture course only for chemistry appear to be overall emotionally unsatisfied with the subject of chemistry towards the end of semester. Based on the responses and results of the matched pairs-t test, it was found that students begin the semester with a feeling of being comfortable with chemistry and then they statistically significantly become uncomfortable towards the end of the semester.

Table 10: Bauer pre- and post-test Chemistry 167 students.

ASCI v2 Item	Pre-test		Post-test		Statistical Significance		
	Mean	S.D.	Mean	S.D.	t-ratio	DF	Prob>|t|
Easy-Hard	4.12	1.26	4.49	1.29	4.09	252	<.0001*
Complicated - Simple	3.77	1.24	3.64	1.34	-1.38	252	0.1662
Confusing - Clear	4.30	1.30	3.98	1.35	-3.13	252	0.0020*
Challenging –Not challenging	3.38	1.28	3.36	1.45	-0.16	252	0.8738
Comfortable-Uncomfortable	3.62	1.39	3.89	1.32	2.74	252	0.0065*
Satisfying-frustrating	3.84	1.26	4.14	1.44	2.98	252	0.0031*
Pleasant-Unpleasant	3.92	1.20	4.34	1.23	5.04	252	<.0001*
Chaotic-Organized	4.85	1.53	4.60	1.52	-2.21	252	<.0277*

* α=0.05

In case of the students who concurrently took Chemistry 167 and Chemistry 167 laboratory, the overall student attitude score is statistically significantly positive. Students begin with a low intellectual accessibility and low emotional satisfaction but their overall attitude becomes more positive towards the end of the semester. As summarized in Table 11, students concurrently enrolled in Chemistry 167 and 167L find chemistry to be significantly hard, complicated, confusing and not challenging. Towards the end of the semester the same students rate chemistry to be easy, simple, clear and yet challenging. This attitude of students taking a laboratory course along with the lecture contrasts to the attitudes of the Chemistry 167 students enrolled only in the lecture component of the course. Students enrolled in the laboratory component rated chemistry to be significantly more emotionally satisfying towards the end of the semester.

Table 11: Bauer pre- and post-test Chemistry 167/ 167L students.

ASCI v2 Item	Pre-test		Post-test		Statistical Significance		
	Mean	S.D.	Mean	S.D.	t-ratio	DF	Prob>|t|
Easy - Hard	3.08	1.10	2.94	1.41	-0.89	105	0.3751
Complicated-Simple	3.41	1.13	4.30	1.35	5.93	105	<.0001*
Confusing -Clear	3.64	1.18	4.16	1.26	3.40	105	0.0009*
Challenging-Not challenging	3.47	1.46	3.08	1.41	-2.04	105	0.0436*
Comfortable-Uncomfortable	4.03	1.23	3.10	1.18	-6.63	105	<.0001*
Satisfying -Frustrating	4.22	1.20	3.33	1.26	-5.83	105	<.0001*
Pleasant-Unpleasant	4.41	1.18	3.57	1.40	-5.94	105	<.0001*
Chaotic-Organized	3.66	1.41	3.94	1.85	1.32	105	0.1871

Bauer pre- and post-test comparison of students concurrently enrolled in chemistry 177 and 177 laboratory yielded similar results to that of students enrolled in Chemistry 167 and Chemistry 167 laboratory course as evident from Table 12. Overall, students enrolled in a laboratory course along with the lecture course had significantly better attitudes towards the subject of chemistry as compared to students enrolled only in the lecture component of a chemistry course.

Table 12: Bauer pre- and post-test comparison Chemistry 177/ 177L students.

ASCI v2 Item	Pre-test		Post-test		Statistical Significance		
	Mean	S.D.	Mean	S.D.	t-ratio	DF	Prob>|t|
Easy-Hard	4.20	1.32	3.69	1.33	-5.61	361	<.0001*
Complicated-Simple	3.67	1.29	3.93	1.42	3.04	361	0.0025*
Confusing -Clear	4.27	1.30	4.02	1.39	-2.84	361	0.0046*
Challenging-Not challenging	4.04	1.45	3.77	1.47	-3.00	361	0.0028*
Comfortable-Uncomfortable	3.36	1.38	3.20	1.41	-1.59	361	0.1126
Satisfying-Unsatisfying	3.74	1.42	3.30	1.27	-5.27	361	<.0001*
Pleasant-Unpleasant	4.09	1.32	3.80	1.36	-3.14	361	0.0018*
Chaotic-Organized	3.94	1.51	4.19	1.58	2.34	361	0.0200*

Test of Logical Thinking (TOLT)

In order to determine the formal reasoning ability of students, the Test of Logical Thinking (TOLT) was used. The TOLT was originally developed by Tobin and Capie (1981). Ten items on the TOLT measure formal thinking of students. Two items measure proportional reasoning, the next two measure students' ability to control variables, two questions are about probabilistic reasoning, the next two questions are on correlational reasoning, and the last two questions on the TOLT measure the combinatorial thinking of students (Trifone, 1987; Ahlawat, and Billeh, 1987). Each item on the TOLT (from 1 through 8) is in multiple-choice format, with a sub question that is also in multiple choice format. Students answer the question first and then pick a reason for the answer choice. For example, Problems 1 and 2 and Problems 3 and 4 measure the proportional reasoning ability of students. There are overall 16 questions on the TOLT and questions 17 and 18 require the students to work their response on a separate sheet showing all possible combinations for questions 17 and 18 (Appendix B).

Example: TOLT Problems 1 and 2:

1. Four large oranges are squeezed to make six glasses of juice. How much juice can be made from six oranges?

a. 7 glasses
b. 8 glasses
c. 9 glasses
d. 10 glasses
e. Other

2. What was the reason to your question for answer 1?

a. The number of glasses compared to the number of oranges will always be in ratio of 3 to 2.
b. With more oranges, the difference will be less.
c. The difference in the numbers will always be two.
d. With four oranges the difference was 2. With six oranges the difference would be two more.
e. There is no way of predicting.

In order to analyze student responses for the TOLT, the students score on questions measuring each of the five reasoning modes of formal thinking were added together and the overall mean, standard deviations and confidence intervals were computed using JMP 9.0 for students in Chemistry 167, students concurrently enrolled in Chemistry 167 and 167L, and students concurrently enrolled in 177 and 177L. To determine the differences among the means of the three groups a one-way analysis of variance test (ANOVA) was run. To further determine the differences, among the groups, Tukey's honestly significant difference (HSD) test was performed. All statistical comparisons were done at α=0.05 significance level.

TOLT Problems 1-4

Items 1 and 3 measure the proportional reasoning of students while items 2 and 4 accompany problem 1 and 3, and are students responses to reasons for the answer choices they made for Item 1 and 3 in a multiple choice format. Proportional reasoning is important for students to understand quantitative relationships in chemistry especially for understanding mole-ratios, balanced equations, gas laws, chemical kinetics, thermochemistry, etc. Table 13 provides descriptive statistics of student performance in the three groups for TOLT problems 1-4. Students in Chemistry 167 and 167L and students in Chemistry 177 and 177L have a higher mean as compared to students enrolled in only the lecture component of Chemistry 167.

Table 13: Mean, standard deviation, and confidence intervals for TOLT problems 1-4.

Group	N	Mean	S.D.	Upper 95%	Lower 95%
Chemistry167 Students	253	3.38	0.992	3.26	3.51
Chemistry 167 and167 L Students	106	3.71	0.740	3.57	3.85
Chemistry 177 and 177L students	361	3.57	0.841	3.48	3.65

A one-way ANOVA was used to test the hypothesis about the means of the three groups. When comparing more than two means, an ANOVA is used instead of a two sample t-test. An ANOVA calculates a ratio for variances which are between and within group sum of squares and follows an F-distribution (Hamilton, 1996; Freund, Wilson and Mohr 2010). The null hypothesis under an ANOVA is that all the means are equal, whereas the alternative hypothesis is that at least one mean is different from the means of other groups in the study.

The results of the one-way ANOVA for the TOLT questions 1-4 indicate that there is a statistically significant difference between the means of Chemistry167 lecture students, Chemistry167, 167 L and Chemistry 177, 177L students, $F(2, 717)=6.17$, $p=.002$, $r^2=0.016$. Posthoc analysis using Tukey-Kramer HSD indicated that the students in Chemistry167/167L had statistically significantly higher score on the proportional reasoning questions of the TOLT ($p=0.003$) as compared to students enrolled in only the lecture component of the course. A posthoc comparison of students concurrently enrolled in Chemistry 177/177L also indicated that the students with a concurrent laboratory course scored statistically significantly higher ($p=0.029$) on the proportional reasoning problems of the TOLT (Table 14) when compared to Chemistry 167 lecture-only students ($p=0.278$) at $\alpha=0.05$.

Table 14: One way ANOVA comparison of Chemistry 167, Chemistry 167/167L, and Chemistry 177/177L students for TOLT problems 1 to 4.

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Between groups	2	9.64[a]	4.82	6.17	0.0022*
Within groups	717	560	0.781		
Total	719	570			

TOLT Problem 5 to Problem 8

Problems 5 and 7 of the TOLT measure the ability of students to control variables. The ability of controlling variables is applied in scientific experimentation. When working on laboratory activities, students should be able to identify the dependent and independent variables and study the effect of a variable keeping the other conditions constant. The ability of controlling variables in chemistry is helpful in understanding the synthesis of compounds via chemical reactions, reaction kinetics, and equilibrium processes.

The findings of a one-way ANOVA for TOLT problems 5-8 indicate that the students in the Chemistry 167/167L have a higher mean score as compared to Chemistry 177/177L students and Chemistry 167 students (Table 15).

Table 15: Mean, standard deviation and confidence intervals TOLT problems 5 - 8.

Group	N	Mean	S.D.	Lower 95%	Upper 95%
167 students	253	3.32	1.22	3.16	3.47
167 and 167L students	106	3.45	1.10	3.24	3.66
177 and 177L students	362	3.28	1.11	3.17	3.40

A one-way ANOVA comparison of means for the students in the three groups indicates no statistically significant differences among the means, $F(2,718)=0.854$, p=0.42m $r^2=0.002$. Based on a one-way ANOVA, there is no statistically significant difference between the means of students enrolled in Chemistry 167 lecture, Chemistry 167/167L, and Chemistry 177/177L course for controlling variables.

Table 16: One way ANOVA comparison of Chemistry 167, Chemistry 167 and 167L, and Chemistry 177 and 177L students for TOLT questions 5 to 8.

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Between groups	2	2.25	1.125	0.854	0.4259
Within groups	718	945.45	1.316		
Total	720	948			

TOLT Problems 9 to Problem 12

Questions 9 and 11 on the TOLT measure students' probabilistic reasoning and questions 10 and 12 are student reasons to the answers they marked as their choice for questions 9 and 11. Probabilistic reasoning is helpful in the comprehension of the concepts such as the heat exchange process, the law of conservation of energy, understanding of quantum chemistry for electronic structure, and the kinetic theory of gases. Especially when working on experiments, it is important that students think in terms of the probabilities in order to replicate experiments and determine averages from measurements or data collected during the laboratory.

A summary of mean, standard deviations and confidence intervals for probabilistic reasoning is shown in Table 17 for students in the three groups in study. Students in the Chemistry 167/167L course, have higher mean values (M=3.66, S.D.=0.78) when compared to students who are concurrently enrolled in Chemistry 177/177L (M=3.57, S.D.=0.77) and students enrolled in only the lecture portion of Chemistry 167 (M=3.54, S.D.=0.89).

Table 17: Mean, standard deviation and confidence intervals TOLT question 9-12.

Group	N	Mean	S.D.	Lower 95%	Upper 95%
167 students	253	3.54	0.897	3.43	3.65
167 and 167L students	106	3.66	0.789	3.51	3.82
177 and 177L students	362	3.57	0.774	3.50	3.65

A one-way ANOVA (Table 18) comparison of the means of three groups for probabilistic reasoning shows no significant differences among Chemistry 167, concurrent Chemistry 167/167L and Chemistry 177/177L students, $F(2,718)=0.97$, $p=0.37$, $r^2=0.002$. Posthoc comparisons were not done when the differences between means were not significant. The posthoc tests hold when there is a difference in means as indicated by p-values at α level of 0.05.

Table 18: One way ANOVA comparison of Chemistry 167, Chemistry 167 and 167L, and Chemistry 177 and 177L students for TOLT questions 9 to 12.

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Between groups	2	1.31	0.655	0.970	0.3794
Within groups	718	484.96	0.675		
Total	720	486.28			

TOLT Problems 13 to 16

Problem 13 and 15 on the TOLT measure students' ability to correlate and questions 14 and 16 provide students' reasons for their answers on problem 13 and 15. Correlational reasoning is helpful in chemistry for students to identify the relationships between the variables when solving problems especially on topics that involve reaction stoichiometry, energy transfer processes such as bond enthalpies and the relationship between ionization energies and electron affinities of atoms.

As shown in Table 19, Chemistry 167/167L students have a higher mean (M=3.58, S.D.=0.64) on correlational reasoning when compared to concurrent Chemistry 177/177L students (M=3.47, S.D.=0.75) or Chemistry 167 students (M=3.34, S.D.=0.888).

Table 19: Mean, standard deviation and confidence intervals TOLT problems 13-16.

Group	N	Mean	S.D.	Lower 95%	Upper 95%
167 students	253	3.34	0.888	3.23	3.45
167 and 167L students	106	3.58	0.645	3.46	3.70
177 and 177L students	362	3.47	0.759	3.39	3.45

Further analysis of differences between the means based on a one-way ANOVA test (Table 20) shows that the means are statistically significantly different for the three groups in study $F(2,718)=3.88, p=0.02, r^2=0.010$. Posthoc comparisons of means using Tukey-Kramer's HSD indicated the mean of Chemistry 167/167L students to be statistically significantly higher (0.02) than the mean score on correlational reasoning when compared to chemistry

177/177L (p=0.12) and Chemistry 167 students who were enrolled only in lecture portion (p=0.38).

Table 20: One way ANOVA comparison of Chemistry 167, Chemistry 167 and 167L, and Chemistry 177 and 177L students for TOLT problems 13-16.

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Between groups	2	4.87	2.438	3.88	0.0210*
Within groups	718	451	0.628		
Total	720	456			

TOLT problems 17 and 18

The last two questions measure combinatorial reasoning of students. Students have to determine all the possible combinations as a solution to the last two problems. Combinatorial reasoning in chemistry comes in handy when studying isomers.

The mean scores for problems 17 and 18 along with the standard deviations are provided in Table 21. Students enrolled in both the lecture and the laboratory component of the Chemistry 167 course have a higher mean score on combinatorial reasoning (M=1.60, S.D.=0.60) than students in the other two groups.

Table 21: Mean, standard deviation and confidence intervals TOLT problems 17 and 18.

Group	N	Mean	S.D.	Lower 95%	Upper 95%
167 students	253	1.37	0.731	1.27	1.46
167 and 167L students	106	1.60	0.602	1.48	1.71
177 and 177L students	362	1.52	0.691	1.45	1.59

Findings from a one-way ANOVA (Table 22), show the means for students in the three groups to be statistically significantly different $F(2, 718)=5.57$, p=0.004, $r^2=0.015$. Posthoc comparison of means using Tukey-Kramer HSD showed statistically significant differences between the students enrolled in both the lecture and laboratory portion of

Chemistry 167 ($p=0.009$) when compared to students enrolled in only the Chemistry 167 course ($p=0.51$). Posthoc comparison also indicated that the students concurrently enrolled in Chemistry 177/177L had significantly higher means on combinatorial reasoning ($p=0.021$) than the 167 students in the lecture portion only ($p=0.51$).

Table 22: One way ANOVA comparison of Chemistry 167, Chemistry 167 and 167L, and Chemistry 177 and 177L students for TOLT problems 17 and 18.

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Between groups	2	5.37	2.68	5.57	0.0040*
Within groups	718	346.53	0.48		
Total	720	352			

Interview worksheet problems

Quantitative comparisons of problem solving in stoichiometry and thermochemistry

To study the impact of laboratory instruction on student problem solving in Chemistry, semi-structured, think-aloud protocol interviews were conducted. Students from chemistry 167, 167L and students enrolled in Chemistry 177 and 177L participated in interviews. Participants were asked questions about their background in chemistry and were required to think aloud while working on specific problems on the topics of stoichiometry and thermochemistry. The rationale behind selecting the topics of stoichiometry and thermochemistry are discussed above in the literature review. In addition, the two topics were well covered in the lecture portions of Chemistry 167 and Chemistry 177. Students had sufficient exposure to the content and practice with the homework and quiz problems on these two topics. Students who enrolled for the laboratory portion of chemistry 167 and students who took Chemistry 177 concurrently with lecture did experiments that were based on the concepts of stoichiometry and thermochemistry.

The interview worksheet had two problems about stoichiometry and two problems on thermochemistry. Based on the research review of literature, researchers have established that students can solve algorithmic problems without understanding the concepts (Nurrenbern, and Pickering ,1987). The interview worksheet was designed keeping in view the prior research (O'Konnell, and Murphy, 2010; Burdge, 2009). The problems on the interview worksheets were intentionally selected so that students got an opportunity to show their problem-solving skills on a simple conceptual problem on each of the two topics followed by a complex problem that is more application-based. In other words, the problems given to students on the interview worksheet require conceptual understanding and cannot be solved by rote memorization of a formula.

In order to answer the research question about problem solving skills of students, the two problems about stoichiometry and thermochemistry on the interview worksheets of students were graded based on a rubric that was developed during interview feedback from the professors who taught the Chemistry 167 and Chemistry 177 courses (Appendix C).

Problems in stoichiometry

Problem 1: (6 points)

What mass of oxygen is needed to completely combust 1.00 grams of ethanol to produce carbon-dioxide and water vapor?

In order to solve problem 1 about stoichiometry students should be:

a) aware of the molecular formula of ethanol
b) able to write a balanced chemical equation for the combustion of ethanol with oxygen;
c) able to identify which reactant is limiting;
d) aware to use the molar mass of ethanol to find the moles of ethanol as a reactant;

e) able to find grams of oxygen that would be used per 1 gram of ethanol that is combusted using reaction stoichiometry.

Based on the frequency distribution of students, it appears that more students in the concurrent lecture and laboratory course were able to complete the problem as compared to students enrolled in only the lecture portion of general chemistry (Table 23).

Table 23: Score frequencies for stoichiometry problem 1.

Scores Possible on stoichiometry Problem 1	Score Frequencies for students with concurrent lecture and laboratory	Score Frequencies for students enrolled only in lecture component of general chemistry
6	10	6
5	3	2
4	3	5
3	3	2
2	3	3
1	0	0

Student response on problem 1 in stoichiometry was compared for all the students who were enrolled in a laboratory course concurrently with lecture using a nonparametric Wilcoxon Test (Table 24). The Wilcoxon test is an equivalent to parametric t-test for paired samples and non-parametric Mann-Whitney-U test which is similar as t-test for independent samples (Corder, and Foreman, 2009). The difference between the parametric and non-parametric tests is that since the distribution is not assumed to be normal, instead of comparing the means, the observations are compared by ranking the data. In such a case the null hypothesis is stated to be no difference between the tendency of ranks in a group being higher or lower than those for observations in another group. The alternative hypothesis may be stated for stoichiometry problem 1 that the ranks of students enrolled in lecture and laboratory course concurrently are systematically higher or lower than those of the students enrolled only in the lecture portion of chemistry. In summary the comparison is done for the distribution instead of comparing the mean differences between the two groups in the study.

A Wilcoxon test was conducted to evaluate whether concurrent laboratory enrollment has an effect in student problem solving. The results indicate no statistical significant difference between the median score of students who took only the lecture portion of general chemistry when compared to students, who took lecture and laboratory course concurrently, z = -0.665, p>0.50, r=0.10 (Table 24).

Table 24: Means and standard deviations stoichiometry problem 1.

	N	Mean	S.D.	Median Score	Mean Rank	Sum of Ranks	Sum of rank scores (S)	Z	prob>|Z|	Effect Size (r)
Lecture group	18	4.33	1.49	4.0	19.16	345	345	-0.665	0.505	0.10
Lab. + Lecture group	22	4.64	1.52	5.0	21.59	475				

Problem 2: (12 points)

Octane (C_8H_{18}) is a component of gasoline. Complete combustion of octane yields H_2O and carbon-dioxide. Incomplete combustion produced H_2O and CO, which not only reduces the efficiency of the engine using the fuel but is also toxic. In a certain test run, 1.000 gallon (gal) of octane is burned in an engine. The total mass of CO, CO_2 and H_2O produced is 11.53 Kg. Calculate the efficiency of the process; that is, calculate the fraction of octane converted to CO_2. The density of octane is 2.650 Kg/gal.

In order to solve problem 2 in stoichiometry students should be able to:

a) Write the balanced chemical equation for complete combustion and incomplete combustion reactions.

b) Use volume and density to find the mass of octane and then find the moles of octane that were burned.

c) Find moles of the products of incomplete and complete combustion to calculate the moles of CO_2 and the moles of CO that would form.

d) Find the amount of products actually formed by difference and then compute the fraction of octane that was completely burned to calculate the percent efficiency.

Frequency distributions for scores of stoichiometry problem 2 (Table 25) shows that students enrolled in concurrent lecture and laboratory as well as students enrolled only in the lecture were not able to solve problem 2 correctly. The students enrolled in both the lecture and laboratory had better scores as compared to students enrolled only in lecture.

Table 25: Score frequencies for stoichiometry problem 2.

Score Possible for Stoichiometry Problem 2	Score Frequencies for students enrolled in lecture and laboratory concurrently	Score Frequencies for students enrolled only in general chemistry lecture course
12	0	0
11	0	0
10	1	0
9	1	1
8	7	1
7	1	2
6	5	4
5	3	4
4	2	0
3	2	1
2	0	3
1	0	2

Based on the Wilcoxon test, results indicated a statistically significant difference on stoichiometry problem 2 scores between the students enrolled in the lecture and laboratory component, z = -2.05, p=0.04, r=0.32 (Table 26) compared to students only enrolled in lecture.

Table 26: Comparison of students enrolled in a concurrent lecture-laboratory chemistry course with students enrolled in only a lecture course on interview worksheet problem 2 on stoichiometry.

	N	Mean	S.D.	Median Score	Mean Rank	Sum of Ranks	Sum of rank scores (S)	Z	prob>|Z|	Effect Size (r)
Lecture group	18	4.77	2.41	5.0	16.33	294	294	-2.05	0.0402*	0.32
Lab. + Lecture group	22	6.41	1.94	6.0	23.91	526				

Qualitative findings on problems 1 and 2 in stoichiometry

In summary, students taking a laboratory course concurrently with the lecture course in general chemistry have statistically significantly better problem-solving abilities on one of the two interview problem about stoichiometry which is also a complex, application-based problem. However, the quantitative findings are limited as they do not provide a complete picture of actually how students solved the interview worksheet problems. In order to further evidence the differences in the problem solving abilities of the students who concurrently take lecture and laboratory course compared to students who take only the lecture course in general chemistry, student worksheets and their interview data was analyzed for any major trends in problem solving among the two groups of students. The major findings of the interview data are summarized below for student responses to stoichiometry problems.

Chemistry background of students concurrently enrolled in lecture and laboratory courses for general chemistry*:*

Students enrolled in general chemistry lecture and laboratory course as well as students enrolled only in the lecture course have a high school chemistry background. In both the groups, students reported having at least one year high school chemistry background and some prior high school laboratory experience.

Stoichiometry problem 1

> What mass of oxygen is needed to completely combust 1.00 grams of ethanol to produce carbon dioxide and water vapor?

Molecular formula for ethanol

Students in the lecture and laboratory as well as the lecture-only group students were able to work on most parts of stoichiometry problem 1. It was found that all the students needed help with the formula of ethanol irrespective of the groups to which they belonged. They either looked up for the formula of ethanol on the Internet or referred to their text in order to set up their equation for the reaction of ethanol with oxygen. Some students in each group used incorrect molecular formula of ethanol. Among the students in the concurrent lecture and laboratory group two students used incorrect molecular formulas C_3H_8 and C_2H_6 for ethanol (C_2H_5OH). Among the students enrolled in only in the general chemistry lecture, two students used C_2H_6 as the molecular formula of ethanol and one student used CH_3COOH which is also incorrect.

Writing and balancing the chemical equation

Writing a balanced chemical equation was the hardest part for students in both of the groups. However, as evident from interview transcripts and worksheet solutions, students in the concurrent lecture and laboratory group were able to balance the equations quickly and correctly as compared to students taking only the lecture component of the course. Students who incorrectly calculated the mass of oxygen required made errors on correctly balancing the chemical equation for the reaction of ethanol with oxygen.

A summary of students who correctly balanced chemical equations and patterns for the student errors in both the concurrent lecture and laboratory students and lecture only students is shown in Table 27. The response highlighted by an asterisk is the correctly balanced equation for stoichiometry problem 1. Majority of students (15) in the concurrent laboratory and lecture course balanced the equation correctly, but they did not either include the states of the reactants and the products or made an error. About 50% of students enrolled only in the lecture course balanced the equation correctly but did not include the state of the reactants and the products which is the correct way to represent a chemical reaction.

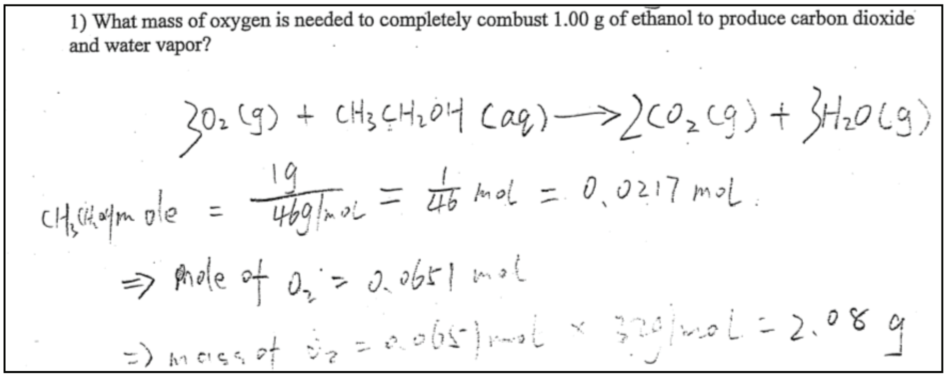
Table 27: Student responses on balanced chemical equation for the reaction of ethanol with oxygen for stoichiometry problem 1.

Balanced equation for chemical reaction as presented by concurrent general chemistry lecture and laboratory students	Number of students (N=22)	Balanced equation for chemical reaction as presented by students enrolled only in lecture portion of general chemistry	Number of students
$3O_2 + C_2H_6O \rightarrow 2CO_2 + 3H_2O$	12	$3O_2 + C_2H_6O \rightarrow 2CO_2 + 3H_2O$	9
*$3O_{2(g)} + C_2H_6O_{(l)} \rightarrow 2CO_{2(g)} + 3H_2O_{(g)}$	1	$O_2 + C_2H_5OH \rightarrow 2CO_2 + 3H_2O$	1
$3O_{2(g)} + C_2H_6O_{(g)} \rightarrow 2CO_{2(g)} + 3H_2O_{(g)}$	1	$2C_2H_6O + 6O_2 \rightarrow 4CO_2 + 6H_2O$	1
$3O_{2(g)} + CH_3CH_2OH_{(aq.)} \rightarrow 2CO_{2(g)} + 3H_2O_{(g)}$	1	$6O_{2(g)} + 2(C_2H_5OH)_{(l)} \rightarrow 4CO_{2(g)} + 6H_2O$	2
$4O_{2(g)} + C_2H_5OH_{(l)} \rightarrow 2CO_{2(g)} + 3H_2O_{(g)}$	1	$C_2H_5OH \rightarrow 2CO_{2(g)} + 3H_2O$	1
$2C_2H_5OH + 5O_{2(g)} \rightarrow 2CO_{2(g)} + 6H_2O$	1	$CH_3COOH + 2O_2 = 2CO_2 + 2H_2O$	1
$12O_{2(g)} + 2(C_2H_5OH)_{(l)} \rightarrow 4CO_{2(g)} + 6H_2O$	1	$2CH_3CH_2OH + 7O_{2(g)} \rightarrow 4CO_2 + 6H_2O$	1
$O_2 + C_2H_5OH \rightarrow 2CO_2 + 3H_2O_{(l)}$	1	$2C_2H_6 + 7O_{2(g)} \rightarrow 4CO_2 + 6H_2O$	1
$O_{2(g)} + C_2H_5OH_{(l)} \rightarrow CO_{2(g)} + 3H_2O$	1	$2C_2H_6 + 7O_{2(g)} \rightarrow CO_2 + 3H_2O$	1
$1C_3H_{8(l)} + 5O_{2(g)} \rightarrow 3CO_{2(g)} + 4H_2O_{(g)}$	1		
$2C_2H_6 + 7O_{2(g)} \rightarrow CO_2 + 3H_2O$	1		

* correct equation

Calculations involved

Among the students in the concurrent lecture and laboratory group who correctly calculated the final answer to be 2.08 grams of oxygen for 1.00 grams of ethanol, they converted the grams of ethanol to the moles and then calculated the moles of oxygen that would be required for the given moles of ethanol using dimensional analysis and the correct molar mass of ethanol (46.0 grams/1 mole of ethanol). In the next step, students converted moles of oxygen to grams using the correct molar mass for O_2 (32 grams/1 mole O_2). Students from concurrent lecture and laboratory course made errors based on incorrect stoichiometric proportions due to (a) an incorrect balanced equation. (b) an incorrect formula for ethanol (c) incorrect molecular mass of ethanol, or (d) used atomic mass of oxygen (16 grams/ 1mole) instead of molecular mass (32 grams/1mole).


1) What mass of oxygen is needed to completely combust 1.00 g of ethanol to produce carbon dioxide and water vapor?

$3O_2(g) + CH_3CH_2OH(aq) \rightarrow 2CO_2(g) + 3H_2O(g)$

CH_3CH_2OH mole $= \frac{1g}{46g/mol} = \frac{1}{46}$ mol $= 0.0217$ mol.

$\Rightarrow$ mole of O_2 = 0.0651 mol

$\Rightarrow$ mass of O_2 = 0.0651 mol × 32g/mol = 2.08 g

Figure 2: Example of student work from concurrent lecture and laboratory course.

Student think-aloud response on stoichiometry problem 1

> "Actually to solve this problem I think the first step is to write down the equation and so O_2 is the gas so $O_2(g)$ and ethanol is CH_3CH_2OH. So I think that should be the equation so to complete that and then the products will be the carbon-dioxide gas plus the water-vapor it's vapor ok so (g) and then we need to balance that and it means that there are 2 carbons in there, in 1 mole of ethanol so we put 2 in front of the CO_2 and then there will be the 6H in the ethanol so I should put 3 in the, in front of the H_2O and the left with the number of the O, we have 4, 3 and -1 O, 4, 3, 7 minus 1, 6 and a 2 [counting atoms on each side of equation] so it this is, so that's the first step to solve the problem and then we need to know the mole of the 1gram of the ethanol and the moles is equal to so 1 gram would be the, let me see 24, 36 grams per mole [molar mass of ethanol] so it would be the 1 over 46 mole.

On analyzing the interview data from students enrolled in only the lecture component of the course it was found that the errors were consistent among the two groups for the first stoichiometry problem. However, there were two major differences between the students in the concurrent lecture and laboratory course and students enrolled only in the lecture course on this particular conceptual stoichiometry problem. The first difference was that the frequency of the errors was smaller among students who took concurrent lecture and laboratory course. Secondly, students taking only the lecture course struggled in making a connection between the number of moles reacted and the number of moles produced. For example, the proportional reasoning based on the balanced equation for the reaction should be:

> "3 moles of oxygen are required for 1 mole of ethanol so how many moles of oxygen will be needed for 0.0217 moles ethanol (1.00 grams)"?

Students' responses were incoherent and lacked proportional reasoning. One example is shown,

> "1 mole of ethanol per 1 mole of ethanol and 1 mole ethanol per 3 moles of oxygen"

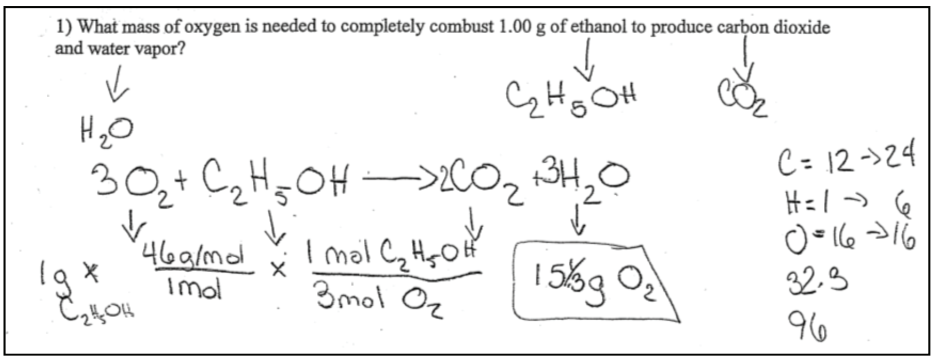


Figure 3: Example of student work from only lecture enrolled students.

Student think-aloud response on stoichiometry problem 1

> "Well, I think, I've got these, these the molar ratio, and that's kind of what's goofing with me a little bit, cause if it was just 1 to 1, I'd need 0.023 moles of oxygen. But, I'm, kind of like, I can't remember exactly what to do if I need to. I think I need to multiply the moles by 2 over 6. I mean, I think that's what I need to do. I kind of [think], I did that wrong, but I wasn't convinced I was right anyway. So then that would be 0.008 [moles of oxygen]. And then, so if that's the moles of oxygen, then I just need to turn that into the mass. So, 0.008 [is] moles of oxygen is O_2, is, so 1 mole for [ethanol], so I just need to multiply that by 31.9988, which is 0.256 and that will be grams [of oxygen]."

Stoichiometry problem 2

Student responses to stoichiometry problem 2 were coded in ATLAS.ti and analyzed for students enrolled concurrently in the laboratory and course and students taking only the lecture portion of general chemistry. It was found that a large number of students in both the groups made errors on this application-based stoichiometry problem and were unable to solve it 100% correctly. In the concurrent lecture and laboratory course group, only one student reached a solution to the problem but had conversion errors in the overall solution to the problem that required several conversions between mass to moles based on the balanced chemical equations for complete and incomplete combustion of a gallon of octane. Among the students taking only the lecture course in general chemistry, only one student reached the solution to the problem but lacked conversions from grams to moles of octane and did not show the work using proper units (dimensional analysis approach).

Problem Statement

When reading aloud the problem statement students struggled with the process of complete and incomplete combustion. Students in both the groups in this research study interpreted the problem statement incorrectly and were unsure if the complete combustion occurred or incomplete combustion of octane occurred. Students struggled with the information given in the problem statement and indicated that some of the information in the problem statement such as the density was irrelevant. They also wanted more information about the mass of the individual products (H_2O, CO_2 or CO) besides the total mass of three products (11.53 kilograms) provided in the problem statement to help them solve for the efficiency of the process

Example of a student response on problem statement from (lecture and laboratory group),

> "We are trying to find the efficiency of the process, same equation like the percent yield kind of thing and what just threw me off is that the total amount of carbon monoxide, carbon dioxide and water is 11.53 kilograms. What I am trying to figure out is how would I like convert that to individual mass of each one of those products. I think, I don't know… if I can get the individual masses and then I was given this information, incomplete combustion I guess, so this kind of threw me off that I had to recollect what kind of molecular equation I could base my calculation on because incomplete combustion will produce water and carbon monoxide."

Example of student response on problem statement from lecture only group:

> I'm thinking efficiency so I'm thinking it would be mass, mass of the like, the quantity in question over like a total mass. So, I am thinking I shouldn't have 2 equations but at the same time like there's 2 different things going on here [complete and incomplete combustion], but I don't know if it should be 1 equation where the reactants should just be octane and oxygen and the products should be water, CO_2 and carbon monoxide all in one. So, I'm just like trying to think about that and like, I can't like, think about it in the right way right now. And I have I know have mass here, I know the density of octane, I don't know what that gives me but, but if, if the density of octane is this and it produces all of these things, the mass, if 1 gallon is burned, the molar mass of these three things should be the same as like, 11.53 should be the same for both sides because it has to have equal masses. So I guess, I don't really know how density fits in here.

Writing and balancing chemical equations

Much of student solutions to problem solving in stoichiometry depends on their understanding of the law of conservation of mass and application of the law in correctly balancing equations for chemical processes. Students provided different responses for this particular problem on the reaction stoichiometry for the complete and incomplete combustion of octane with a large number of students attempting two separate equations for complete and incomplete combustion.

Student response on the second stoichiometry problem is consistent with their response on balancing the equation for the first problem on stoichiometry, with the exception being that students were provided the formula for the reactant in this problem so errors with the molecular formula of octane were not observed. However, the errors with using the proportional reasoning to balance the reactions were consistent among the students in the concurrent lecture and laboratory group and the students enrolled in only the lecture course for general chemistry. Student responses on balanced equations for the complete combustion of octane and reaction for the incomplete combustion of octane are summarized in Table 28. Students enrolled in the concurrent lecture and laboratory group had the maximum correct responses for balanced equations (14/22) for complete combustion of octane when compared to students in the lecture-only group who attempted the equation for complete combustion (11/18). For incomplete combustion of octane more students (8/18) who took only lecture course correctly balanced the reaction equation for incomplete combustion than students in the concurrent lecture and laboratory group.

Table 28: Equations for complete and incomplete combustion of octane.

Balanced equation for chemical reaction as presented by concurrent general chemistry lecture and laboratory students (Summary of two equations written by each student)	Number of students	Balanced equation for chemical reaction as presented by students enrolled only in lecture portion of general chemistry	Number of students
Complete combustion			
$2C_8H_{18} + 25O_2 \rightarrow 18H_2O+16CO_2$	10	$2C_8H_{18} + 25O_2 \rightarrow 18H_2O+16CO_2$	10
$2C_8H_{18} + 25/2O_2 \rightarrow 9H_2O+8CO_2$	4	$C_8H_{18} + 12.5O_2 \rightarrow 9H_2O+8CO_2$	1
Incomplete combustion			
$2C_8H_{18(g)} + 17O_{2(g)} \rightarrow 18H_2O_{(g)}+16CO_{(g)}$	5	$2C_8H_{18}+ 17O_2 \rightarrow 18H_2O+16CO$	7
		$C_8H_{18}+ 8.5O_2 \rightarrow 9H_2O+8CO$	1

Calculations

More students in the concurrent lecture and laboratory group moved past the step of balancing the reaction equations and calculated the amount of CO_2 and H_2O that would form when there is a complete combustion of 1.0 gallon of octane. The most important factor to consider in solving this problem is to take note of the overall mass of products given in the problem statement (11.53 Kg) and then compare it to the mass of products that would result with the complete combustion (11.9 Kg). The ratio of mass of products of incomplete combustion and the mass of products for incomplete combustion leads to the percent of octane that undergoes combustion (97%) based on the information given in the problem. Students from the lecture portion of the course attempted to solve the problem by taking the mass of carbon monoxide as x moles without paying attention to the moles of the products that would form for complete combustion and the starting moles of the reactants.

Based on qualitative interview data, it was found that students in the concurrent laboratory and lecture course used dimensional analysis to set up problem 2 for stoichiometry correctly based on their correct balanced equations. However lecture-only students who had correct balanced equation did not pay much attention to the mole ratios, avoided using the dimensional analysis method to solve for the moles of products that would form for complete and incomplete combustion and ignored the units. Instead they approached the problem very much in an algorithmic manner by trying to calculate the value of “x” for the reactant octane or “x” gram of carbon monoxide as one of the products of incomplete combustion

Example of student’s solution to stoichiometry problem 2 from concurrent lecture and laboratory group:

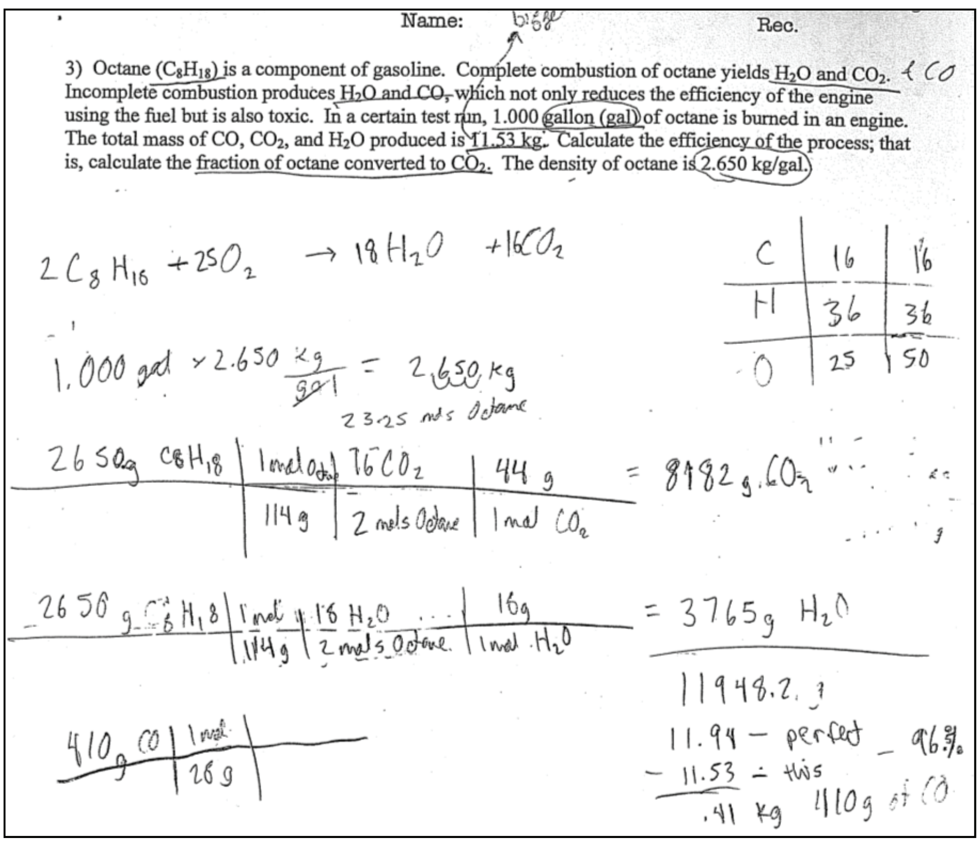
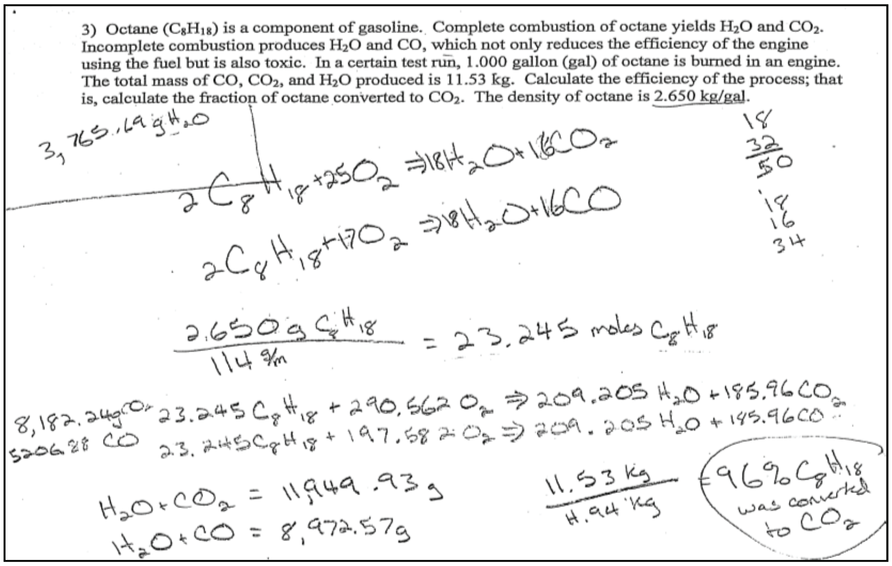


Figure 4: Solution to stoichiometry problem 2 from student in the concurrent lecture and laboratory general chemistry courses.

Example of a student's solution to stoichiometry problem 2 from student enrolled only in lecture portion of general chemistry:


3) Octane (C_8H_{18}) is a component of gasoline. Complete combustion of octane yields H_2O and CO_2. Incomplete combustion produces H_2O and CO, which not only reduces the efficiency of the engine using the fuel but is also toxic. In a certain test run, 1.000 gallon (gal) of octane is burned in an engine. The total mass of CO, CO_2, and H_2O produced is 11.53 kg. Calculate the efficiency of the process; that is, calculate the fraction of octane converted to CO_2. The density of octane is 2.650 kg/gal.

3,765.69 g H_2O

$2C_8H_{18} + 25O_2 \Rightarrow 18H_2O + 16CO_2$

$2C_8H_{18} + 17O_2 \Rightarrow 18H_2O + 16CO$

18 32 50

18 16 34

$\frac{2.650\text{ g } C_8H_{18}}{114\text{ g/m}} = 23.245$ moles C_8H_{18}

8,182.24 g CO_2

5206.28 CO

$23.245\,C_8H_{18} + 290.562\,O_2 \Rightarrow 209.205\,H_2O + 185.96\,CO_2$

$23.245\,C_8H_{18} + 197.582\,O_2 \Rightarrow 209.205\,H_2O + 185.96\,CO$

$H_2O + CO_2 = 11,949.93$ g

$H_2O + CO = 8,972.57$ g

$\frac{11.53\text{ kg}}{11.94\text{ kg}}$ = 96% C_8H_{18} was converted to CO_2

Figure 5: Solution to stoichiometry problem 2 from student enrolled only in lecture portion.

Problems on thermochemistry

Problem 1: (6 points)

What is the final temperature (in °C) when 1 gallon of water evolves 118.8 kJ of heat when it cools from 32.5°C?

In order to solve problem 1 on thermochemistry students should be able to:

a) Convert 1 gallon of water to liters and Kilojoules to Joules.

b) Apply their understanding of the relation between the amount of heat exchanged (q) between the water and the surroundings (water gives up heat and cools down) that is q=mass x specific heat of water x change in temperature.

c) Determine the final temperature, guessing from the problem statement that T_{final} would be smaller than the $T_{initial.}$

Students' taking concurrent lecture and laboratory general chemistry course did better on problem 1 of thermochemistry when compared to students enrolled only in the lecture component of general chemistry. A large percent of students in the lecture and laboratory course solved the first problem about thermochemistry completely and correctly (10/22 students) as compared to students enrolled only in lecture course (2/19) for general chemistry (Table 29).

Table 29: **Score Frequencies for problem 1 on thermochemistry.**

Scores Possible on stoichiometry Problem 1	Score Frequencies for students with concurrent lecture and laboratory	Score Frequencies for students enrolled only in lecture component of general chemistry
6	10	2
5	3	5
4	5	2
3	1	3
2	1	2
1	2	5

On comparing student performance on problem 1 of thermochemistry using the non-parametric Wilcoxon test, it was found that the students in concurrent laboratory and lecture group did statistically significantly better than students, who did not take a concurrent general chemistry laboratory course, z = -2.62, p=0.008, r=0.41 (Table 30).

Table 30: Comparison of students with a concurrent lecture-laboratory chemistry course with students enrolled in only a lecture course for interview worksheet problem 1 on thermochemistry.

	N	Mean	S.D.	Median Score	Mean Rank	Sum of Ranks	Sum of rank scores (S)	Z	prob>|Z|	Effect Size (r)
Lecture group	18	3.17	1.76	3	15.22	274	274	-2.62	0.0087*	0.41
Lab. + Lecture group	22	4.63	1.65	5	24.81	546				

Problem 2: (12 points)

One of the most popular approaches to dieting in recent years has been to reduce dietary fat. One reason many people want to avoid easting fat is its high calories content. Compared to carbohydrates and proteins, each of which contains an average of 4 Calories per gram (17kJ/g), fat contains 9 Calories per gram (38 kJ/ g). Tristearin a typical fat, is metabolized (or combusted) according to the following equation:

$C_{57}H_{110}O_{6\,(s)} + 81.5O_{2\,(g)} \rightarrow 57CO_{2\,(g)} + 55H_2O_{\,(l)}$ $\Delta H = -\ 37{,}760$ KJ/mole

Although the food industry has succeeded in producing low-fat versions of nearly everything we eat, it has thus failed to produce a palatable low fat doughnut. The flavor, texture and what the industry calls "mouth-feel" of a doughnut depends largely on the process of deep fat-frying. Fortunately for people in the doughnut business, though, high fat content has not diminished the popularity of the doughnuts. According to the information obtained from www.krispykrememe.com a Krispykreme original glazed doughnut weighs 52 grams and contains 200 Calories and 12 grams of fat.

a. Assuming that the fat in the doughnut is metabolized according to the given equation for tristearin, calculate the number of Calories in the reported 12 grams of fat in each doughnut**.**

b. If all the energy contained in a Krispykreme doughnut (not just the fat) were transferred to 6.00 kilograms of water originally at 25.5 °C, what would be the final temperature of the water?

c. When a Krispykreme apple fritter weighing 101 g is burned in a bomb calorimeter with the C_{cal}=95.3 kJ/°C, the measured temperature increase is 16.7 °C. Calculate the number of Calories in a Krispykreme apple fritter.

d. What would the ΔH° value be for the metabolism of 1 mole of the fat tristearin if the water produced by the reaction was gaseous instead of liquid?

In order to solve the second problem on thermochemistry students should be able to-

a) Draw the relationships using information in the problem statement.

b) Find the moles of fat Tristearin based on the grams of fat.

c) Used information from the balanced equation to calculate the Calories.

d) Use appropriate conversion factors (1 small calorie=4.184 Joules).

e) Use the relation between the heat exchanged between the doughnut and water, understanding that the doughnut transfers heat to water so the final temperature will be higher than the initial temperature in part b of the problem.

f) Understand that part c of the problem is about bomb calorimetry which is different from constant pressure calorimeter. The solution to part c of the problem will require knowledge of constant volume and the use of the relation that heat exchanged (q)=

calorimeter constant x change in temperature. Further it requires use of the conversion factor 1Calorie=4.184 kJ.

g) Infer that the change in enthalpy (ΔH°) for combustion of 1 mole of tristearin will change with the change in the state of one of the products (water from being gaseous to liquid) for the reaction for the metabolism of tristearin.

The second problem on thermochemistry was a complicated problem. Students only answered some parts of the problem. In order to compare student performance among the concurrent lecture and laboratory students with students enrolled in only the lecture portion of general chemistry, student scores were summed for all four parts of problem 2 in thermochemistry. Table 31 provides a summary for the frequencies of student scores. As can be seen, students in both the groups in the study were unable to provide a complete solution for the application-based problem. One reason could be that it required a lot of conversions and the stoichiometric proportions in the balanced equation for the metabolism of the fat tristearin were too large. However more students in the laboratory and lecture attempted problem 2 on thermochemistry when compared to students enrolled only in the lecture component.

Comparison of student performance on this application-based thermochemistry problem was done using Wilcoxon Test (Table 32) which indicated no statistically significant differences between the students who concurrently took the general laboratory and lecture course and students who only took the general chemistry lecture course, $z = -1.93$, $p=0.05$, $r=0.30$.

Table 31: Score frequencies for thermochemistry problem 2.

Score Possible for Stoichiometry Problem 2	Score Frequencies for students enrolled in lecture and laboratory concurrently	Score Frequencies for students enrolled only in general chemistry lecture course
12	0	0
11	0	0
10	0	0
9	0	0
8	2	0
7	5	0
6	1	1
5	2	2
4	1	3
3	8	7
2	3	3
1	0	2

Table 32: Comparison of students with a concurrent lecture-laboratory chemistry course with students enrolled in only a lecture course on interview worksheet problem 2 on thermochemistry.

	N	Mean	S.D.	Median Score	Mean Rank	Sum of Ranks	Sum of rank scores (S)	Z	prob>|Z|
Lecture group	18	3.16	1.40	3.0	16.64	299.5	299.5	-1.93	0.0530
Lab. + Lecture group	22	4.59	2.13	3.5	23.66	520.5			

Overall the students who took both the lecture and the laboratory component for general chemistry did statistically significantly better on at least two out of four interview worksheet problems, still the students in both groups struggled with the second problem on stoichiometry and thermochemistry. Based on the mean score, it is apparent that though the students in the concurrent lecture and laboratory group performed significantly better than the students who only took the lecture, they did not solve the entire problem correctly and majority of them had an average score that represents incomplete solution to the problems on interview worksheets.

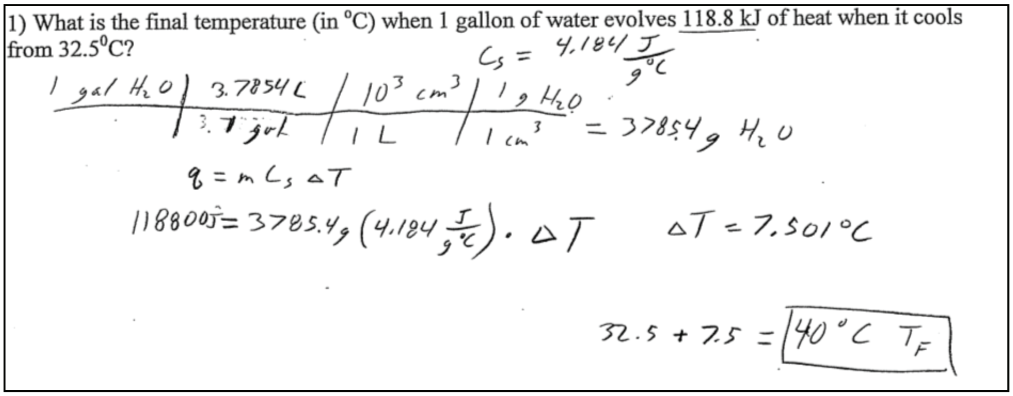
Thermochemistry Problem 1: Qualitative analysis

Analysis of the interview data for thermochemistry problem 1 of reveals an interesting pattern. In order to solve this problem correctly, students need to convert 1.0 gallon of water to kilograms and then to grams. On analysis of student worksheets it was found that at least 10 students did not show any proper use of units and conversion factors involved. So even though their answers were correct they lacked proper units and conversions that impacted their overall score in the quantitative comparisons based on the grading rubric.

Among the students in both the concurrent lecture and laboratory courses and from the lecture only course who attempted problem 1 of thermochemistry, some of the students made a common error of incorrectly interpreting water to be gaining and not losing heat. These students reported the final temperature incorrectly as higher (40 °C) from the initial temperature of water to be 32.5 °C as stated in the problem. In addition students tried a plug and chug approach to solve this conceptual problem involving heat exchange between water and the surroundings. They set up the equation to be as:

Heat exchanged, q=mass of water x specific heat of water x ΔT (T_{final}-$T_{initial}$)

On calculation these students found that ΔT=q in unit of Joules x Specific heat of water which equals 4.18 Joules per gram °C divided by the the heat exchanged (q) in units of Joules. These students obtained correct ΔT (7.5 °C) but failed to logically connect to the statement that water is evolving heat and hence cooling down so the final temperature should be smaller than the initial temperature (32.5°C) and incorrectly added 7.5 to the initial temperature obtaining a final temperature of 40°C) (Figure 6).



1) What is the final temperature (in °C) when 1 gallon of water evolves 118.8 kJ of heat when it cools from 32.5⁰C?

$C_s = 4.184 \frac{J}{g°C}$

$\frac{1 \text{ gal } H_2O}{} \bigg| \frac{3.7854 L}{3.7 \text{ gal}} \bigg| \frac{10^3 cm^3}{1 L} \bigg| \frac{1 g H_2O}{1 cm^3} = 3785.4 g \, H_2O$

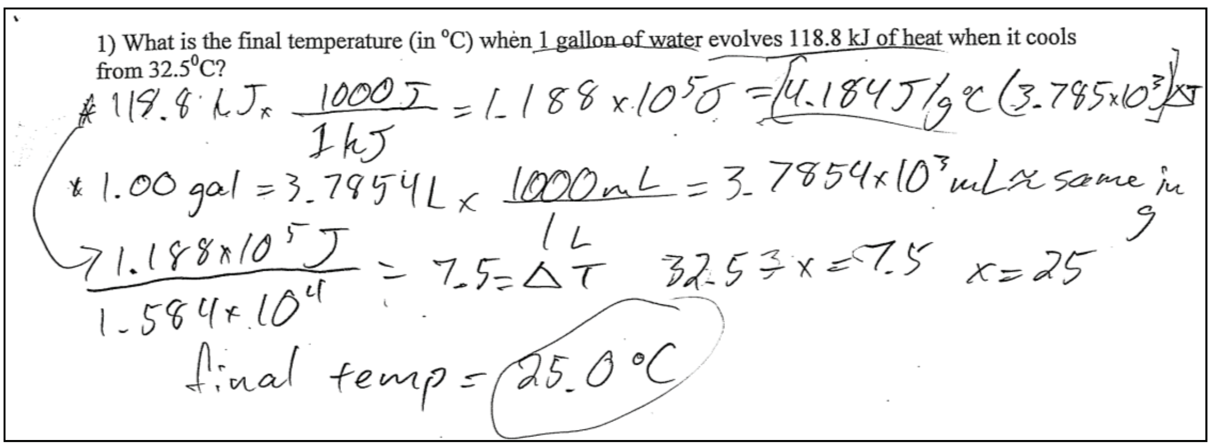
$q = m C_s \Delta T$

$118800 J = 3785.4 g \left(4.184 \frac{J}{g°C}\right) \cdot \Delta T \qquad \Delta T = 7.501°C$

$32.5 + 7.5 = \boxed{40°C \; T_F}$

Figure 6: Incorrect student response to problem 2 of thermochemistry.

Example of a student solution for thermochemistry problem 1 from concurrent lecture and laboratory course and only lecture course is given below:



1) What is the final temperature (in °C) when 1 gallon of water evolves 118.8 kJ of heat when it cools from 32.5⁰C?

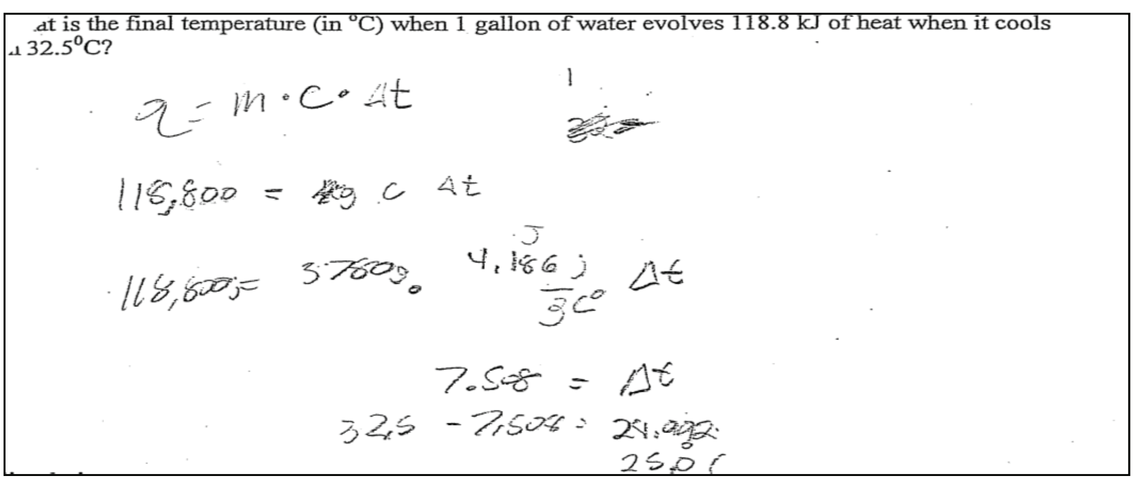
$118.8 kJ \times \frac{1000 J}{1 kJ} = 1.188 \times 10^5 J = [4.184 J/g°C (3.785 \times 10^3)] \Delta T$

$1.00 \text{ gal} = 3.7854 L \times \frac{1000 mL}{1 L} = 3.7854 \times 10^3 mL \approx$ same in g

$\frac{1.188 \times 10^5 J}{1.584 \times 10^4} = 7.5 = \Delta T \qquad 32.5 - x = 7.5 \qquad x = 25$

final temp = 25.0 °C

Figure 7: Student solution of problem 1 on thermochemistry from concurrent lecture and laboratory course.



at is the final temperature (in °C) when 1 gallon of water evolves 118.8 kJ of heat when it cools 32.5⁰C?

$q = m \cdot C \cdot \Delta t$

$118,800 = g \cdot c \; \Delta t$

$118,800 J = 3780 g \cdot 4.186 \frac{J}{g C°} \Delta t$

$7.508 = \Delta t$

$32.5 - 7.508 = 24.992$

25.0 °C

Figure 8: Student solution of problem 1 on thermochemistry from general chemistry lecture only course.

Thermochemistry Problem 2: Qualitative analysis

The second problem in thermochemistry has four parts. The quantitative comparison using Wilcoxon test showed no statistically significant differences among students in the concurrent lecture and laboratory course and students taking only the lecture course of general chemistry. On qualitative analysis of student worksheets and interview transcripts it was found that students felt that this problem was hard. A few patterns observed among concurrent lecture and laboratory students and students taking only the lecture portion of the course are explained as follows.

Part (a) of the second thermochemistry problem requires the students to calculate the number of Calories in the reported 12 grams of fat. Students in both of the groups in study used the relation 12 grams of fat times 9 Calories per 1 gram and calculated the final answer to be 108 Calories. The correct solution of the problem requires the conversion of 12 grams of fat to the moles of fat using the molar mass for the chemical formula of tristearin given in the balanced equation. Based on the problem statement, since 1 mole of tristearin produced -37,760 kJ/ 1 mole the correct answer would be 121.68 or 122 kJ/ 12 grams of fat. About 16.67 % (3/18) lecture only enrolled students and 41% (9/22) concurrent lecture and laboratory group students simply calculated 108 Calories and overlooked the mole-ratio for fat. Only 9% students (2/22) from concurrent lecture and laboratory group and 5.55 % (1/18) from lecture only course correctly answered the problem (Figure 9 - Figure 10)

> a) Assuming that the fat in the doughnut is metabolized according to the given equation for tristearin, calculate the number of Calories in the reported 12 g of fat in each doughnut.
>
> 9cal/g · 12g = 108 calories

Figure 9: Incorrect solution as shown by the lecture as well as concurrent lecture and laboratory students.

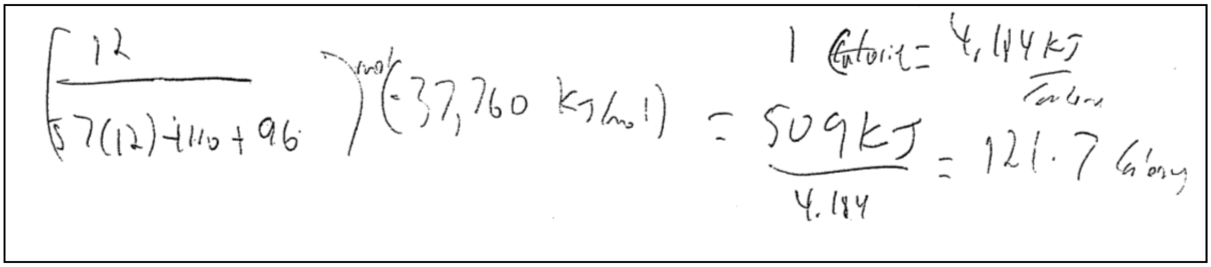
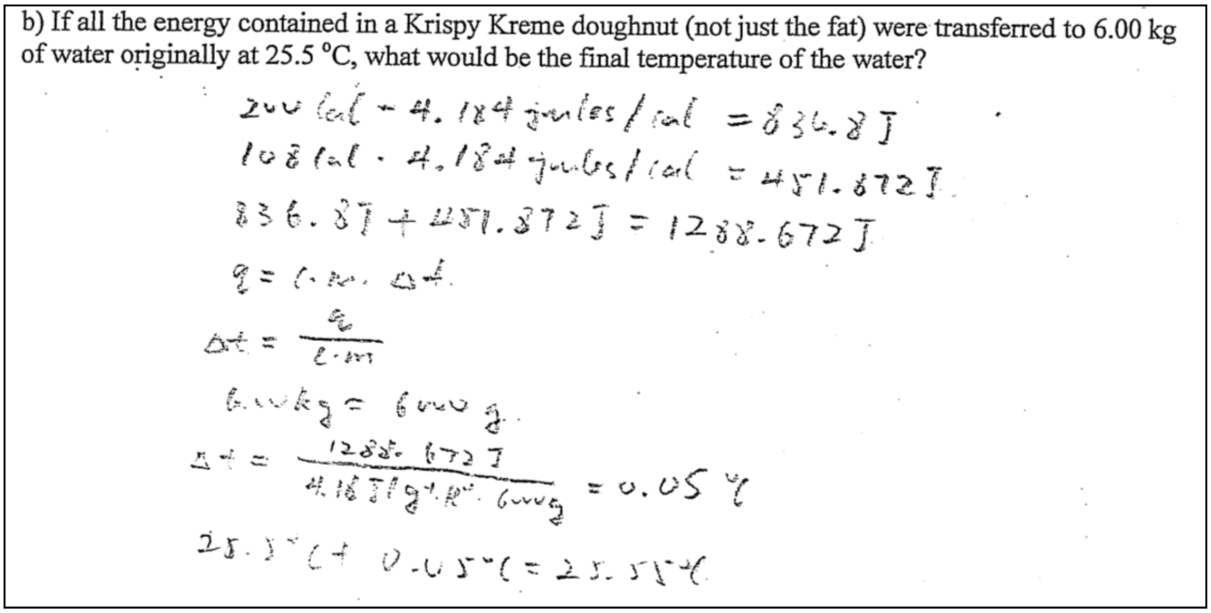


Figure 10: Correct solution as shown by the lecture and concurrent laboratory and lecture students.

Part (b) of thermochemistry problem 2 requires calculation of the final temperature of water when all the energy contained in a Krispy Kreme doughnut is transferred to 6.00 kilograms of water originally at 25.5 °C. The initial temperature is given and the problem states the mass of doughnut equals 52 grams and it contains 200 Calories of energy. In order to solve this problem the mass of water should be converted from kilograms to grams. Specific heat of water needs to be converted from units of Joules (4.184 Joules) to small calories (4.184 J=1 small calorie) and 100 nutritional Calories=100,000 small calories. Using the relation between the heat transferred, mass, specific heat and change in temperature, the equation

q = mass x specific heat of water x change in temperature, the final temperature may be calculated to be equal to 58.8 °C.

The big idea in the solution of this problem is the law of conservation of energy according to which all the energy lost by the doughnut equals the energy gained by the water, thus raising the final temperature of the water. On comparing student interview responses and worksheet solutions, it was found that 22.7% (5/22) students in concurrent lecture and laboratory course and 11% (2/18) students enrolled only in lecture calculated no change for final temperature of water (25.5 °C). The majority of students in concurrent lecture and laboratory groups 54.5% (12/22) and 27.7% (5/18) from lecture only group reported a higher incorrect temperature value for final temperature of water. A few students in both the groups requested to move on to the next part of the problem after an initial conversion of water from kilograms to grams. The examples of student responses for no change of temperature and an example of correct responses are shown in figure 11 and figure 12.


b) If all the energy contained in a Krispy Kreme doughnut (not just the fat) were transferred to 6.00 kg of water originally at 25.5 °C, what would be the final temperature of the water?

200 Cal · 4.184 joules / cal = 836.8 J

108 Cal · 4.184 joules / cal = 451.872 J

836.8 J + 451.872 J = 1288.672 J

q = c · m · Δt

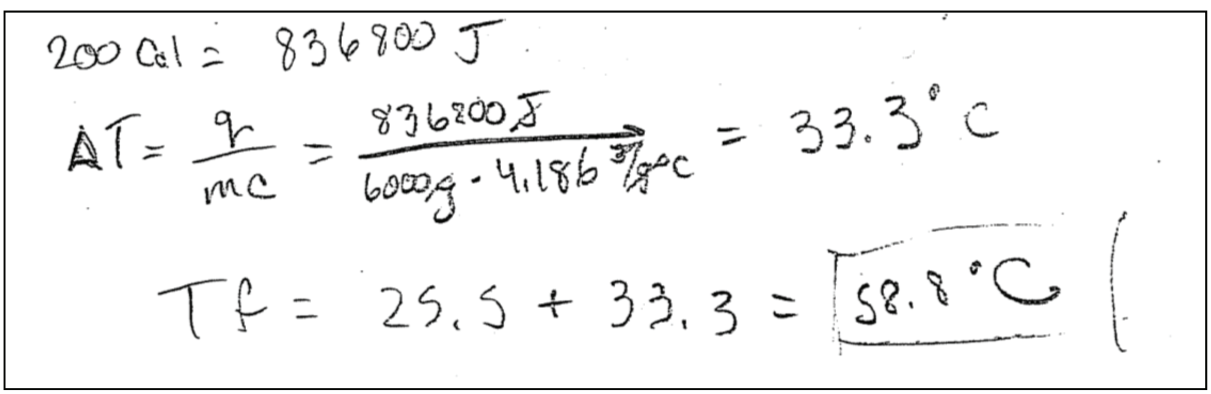
Δt = q / (c · m)

6.00 kg = 6000 g

Δt = 1288.672 J / (4.18 J/g·K · 6000 g) = 0.05 °C

25.5 °C + 0.05 °C = 25.55 °C

Figure 11: No change in final temperature of water as shown by student taking only lecture.


200 Cal = 836800 J

ΔT = q / mc = 836800 J / (6000 g · 4.186 J/g°C) = 33.3 °C

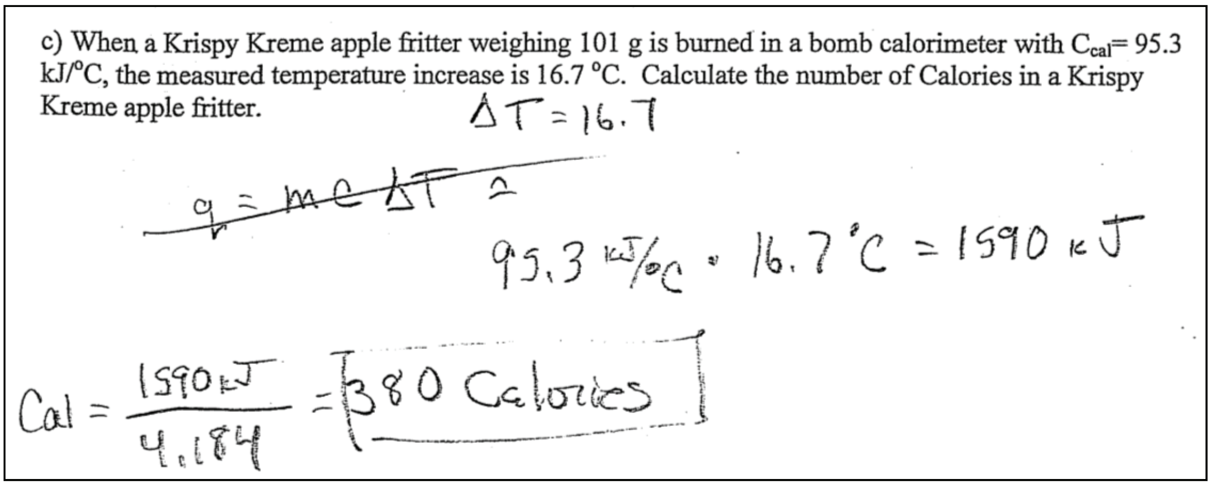
Tf = 25.5 + 33.3 = 58.8 °C

Figure 12: Correct temperature change as shown by lecture only enrolled and concurrent lecture and laboratory students.

Part (c) of the second problem in thermochemistry requires the students to apply the law of conservation of energy using a constant volume bomb calorimeter and an understanding that the breaking and formation of chemical bonds is accompanied by an energy transfer process. According to the problem statement, one needs to calculate the energy in units of Calories contained in a Krispy Kreme apple fritter that weighs 101 grams and is burned in a bomb calorimeter with colorimeter constant (C_{cal}=95.3 kJ/ °C). Since bomb calorimeters are constant-volume calorimeters, the sample in such a calorimeter is burned electrically and the heat released by the combustion of the sample is thus absorbed by water. The change in temperature is obtained from the change in temperature of water. The assumption in the case of bomb calorimetry is that no heat is lost to the surroundings since the calorimeter is considered an isolated system.

The solution for part (c) of thermochemistry problem thus requires the use of the relation between the heat exchanged during the reaction (q_{rxn}.) which is directly proportional to the Calorimeter constant and the change in temperature (or $q_{rxn}=C_{cal} \times \Delta T$) to find the number of Calories (=380.4) Calories).

Analysis of interview transcripts and worksheet solutions indicates that students were confused between the solution calorimetry, which is constant-pressure calorimeter and bomb calorimetry which is a constant-volume calorimetry. Further analysis of student responses indicated that 16.6% (3/18) of the lecture only students did not attempt the problem and requested to pass; 61.1% (11/ 18) students made incorrect calculations and 22.2 % (4/18)) students gave a close but incorrect answer (example, 382.3 Calories). Similar results were obtained on analysis of student transcripts and worksheet solutions for concurrent laboratory and lecture course students .13.6% (3/22) of the students in concurrent laboratory and lecture group did not attempt the problem at all; 13.6% of the students obtained a correct answer but rounded it incorrectly (3/22); 22.7 % (5/22) students had answer that were close to correct answer (377 Calories) and 50% students (11/22) students had completely incorrect answers. On close examination of student errors it was found that most commonly those who had close answers made huge rounding errors and had worked the problem in haste. The students who made significant errors were mainly stuck on the conversion factor between kJ to Calories in both the groups.


c) When a Krispy Kreme apple fritter weighing 101 g is burned in a bomb calorimeter with C_{cal}= 95.3 kJ/°C, the measured temperature increase is 16.7 °C. Calculate the number of Calories in a Krispy Kreme apple fritter.

$\Delta T = 16.7$

$\cancel{q = mc\Delta T}$

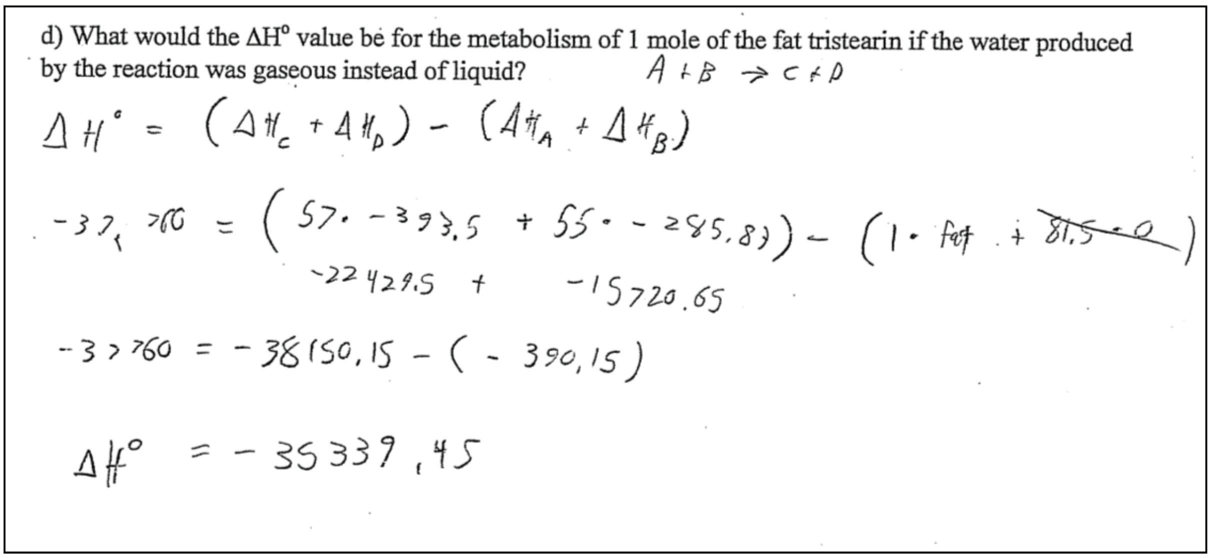
$95.3\ kJ/°C \cdot 16.7\ °C = 1590\ kJ$

$Cal = \frac{1590\ kJ}{4.184} = \boxed{380\ Calories}$

Figure 13: Student solution of problem 2c thermochemistry.

Part (d) of the second thermochemistry problem is based on the change in enthalpy values for the metabolism of 1 mole of the fat tristearin with the change in the state of one of the products such as water changing to the gaseous state from the liquid state. The enthalpy of the reaction will thus become less negative from -37,760 kJ/mol as stated in the reaction equation for metabolism of 1 mole of tristearin, because gaseous water has an enthalpy (ΔH_f) value of -285.8 kJ/mol when compared to liquid water which has an enthalpy (ΔH_f) value of -241.8 kJ/mol thus leading to an enthalpy change to -35,751 kJ.

Analysis of student responses from interview transcripts among the concurrent laboratory and lecture students indicated that 40.0% (9/22) of the students gave up trying on the problem after an initial confusion about increase or decrease in enthalpy value with phase change; 22.7% (5/22) of the students calculated a decrease in enthalpy values which was conceptually correct yet numerically incorrect; and 18.18% (4/22) of the students calculated a higher negative value; and 18.18% (4/22) students calculated a positive enthalpy value which are both incorrect.



d) What would the ΔH^o value be for the metabolism of 1 mole of the fat tristearin if the water produced by the reaction was gaseous instead of liquid? $A + B \rightarrow C + D$

$$\Delta H^\circ = (\Delta H_C + \Delta H_D) - (\Delta H_A + \Delta H_B)$$

$$-37,760 = (57 \cdot -393.5 + 55 \cdot -285.83) - (1 \cdot \text{fat} + \cancel{81.5 \cdot 0})$$

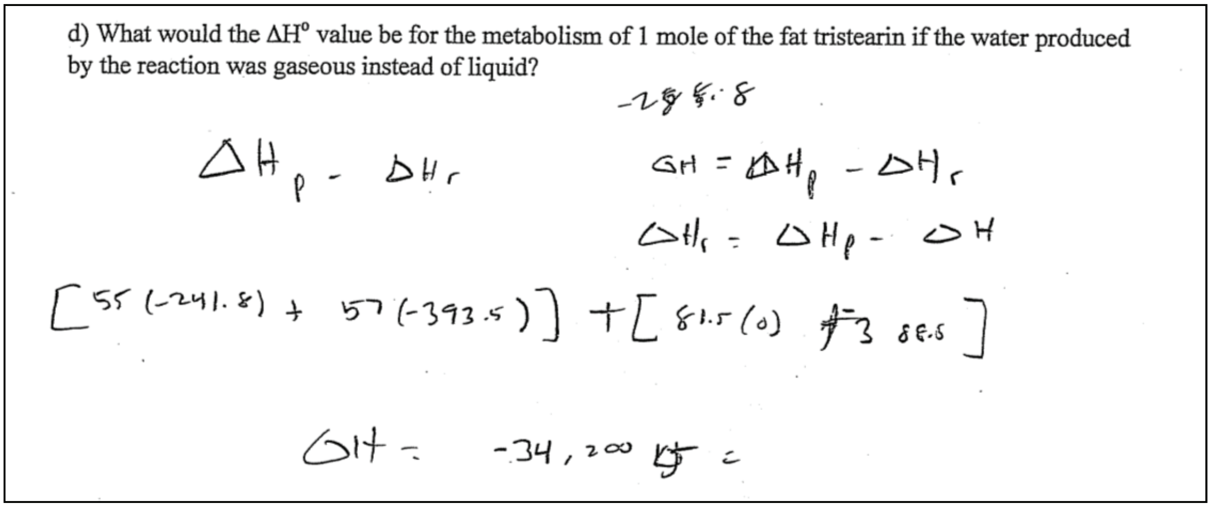
$$-22429.5 + -15720.65$$

$$-37760 = -38150.15 - (-390.15)$$

$$\Delta H^o = -35339.45$$

Figure 14: Student solution of part 2d of thermochemistry from concurrent lecture and laboratory group.

Among students taking only the lecture portion of general chemistry, 33.3% (6/18) students opted to not solve the problem; 16.6% (3/18) students stated that the enthalpy value will stay the same for the metabolism of fat. On further probing, students explained that since the product was still water, the enthalpy values will not change for the reaction; 16.6% (3/18) students stated that the enthalpy values would be higher. These students reasoned that water would change from liquid state to gaseous state so it would release more energy; 11.1% (2/18) of the students calculated the enthalpy values and gave a conceptually correct explanation for the change in enthalpy of water but numerically incorrect response (-34,200 kJ); and 22.2 (4/18) students tried to set up the equation for the change in enthalpy based on the number of moles of water but did not proceed further and backed out.



d) What would the ΔH^{o} value be for the metabolism of 1 mole of the fat tristearin if the water produced by the reaction was gaseous instead of liquid?

-2858.8

$\Delta H_p - \Delta H_r$

$\Delta H = \Delta H_p - \Delta H_r$

$\Delta H_r = \Delta H_p - \Delta H$

$[55(-241.8) + 57(-393.5)] + [81.5(0) \; 3 \; 88.5]$

$\Delta H = -34,200 \text{ kJ} =$

Figure 15: Student solution on problem 2d from the lecture-only group.

The student responses were very much alike for thermochemistry problem 2 among concurrent lecture and laboratory students as well as lecture only students. Students had difficulty in determining the direction of heat flow based on the sign of the enthalpy values which resulted in errors among students who calculated the enthalpy values to be higher or positive numbers. The findings of qualitative data are consistent with the quantitative values in which there are no statistically significant differences between concurrent lecture and laboratory course students when compared to students taking only the lecture portion of general chemistry.

Conclusions

Findings from the qualitative data are consistent with the findings from the quantitative data for problem solving among the students in the concurrent lecture and laboratory course and student taking only the lecture portion of general chemistry. There are statistically significant differences between student attitudes, formal thinking abilities and problem-solving skills among the students in the two groups. It is however worth noting that the students in the concurrent general chemistry laboratory and lecture course comparatively understand the problems better and apply general rules of problem solving such as interpreting the problem statement correctly and setting up the balanced equations for the reactions. Even though the TOLT scores of students on probabilistic and correlational reasoning were not significantly different, it was found that overall the students taking a concurrent lecture and laboratory course show better formal thinking abilities as compared to students taking only the lecture portion of the course. It may be possible that students applied their observations of macroscopic phenomenon in the laboratory to their problem-solving on stoichiometry and thermochemistry during the interview process; however such a comparison was out of the scope for this study.

The findings of this study on the problem-solving skills of students in concurrent lecture and laboratory course tie well with some of the traits of formal operational thinkers listed by Herron (1975). The formal operational thinkers make frequent use of the factor-label method to solve problems where the units provide an indication of the operation to be performed. Herron (1975) also listed that formally developed thinkers can balance equations and calculate molecular weights using set rules.

Quantitative findings of this study show that students taking a concurrent lecture and laboratory course were statistically significantly better at solving problems- the second problem in stoichiometry and first problem in thermochemistry. However, there were no statistically significant differences among the students in concurrent laboratory and lecture only course for problem 1 in stoichiometry and problem 2 of thermochemistry. It is notable that the concurrent laboratory and lecture students had a higher mean score on all the four interview worksheet problems. Students taking both the lecture component and the laboratory component of general chemistry appear to have an advantage over students taking only the lecture course; chemistry placement scores indicated that the students in both groups were equivalent at the beginning of the semester. Based on the quantitative findings supported by qualitative data, there is evidence that student taking first year concurrent general chemistry laboratory and lecture course gain a better understanding of stoichiometry and thermochemistry. These students (a) perform academically better on their hour exams and final exams for the course (b) have a significantly better attitude towards the subject of chemistry (c) developed formal thinking skills and (d) are better in problem-solving skills on specific topics in general chemistry.

Limitations

Some of the limitations of the study include lack of video-data on student interactions when they take the lecture-only component of the course and when a group of student takes both the lecture and laboratory component of the course. Another limitation of this study is the difference in the content. In order to ensure that the comparison was as fair as possible among the groups' only stoichiometry and thermochemistry interview problems were studied.

Another limitation to this study was a lack of interview data from students who took lecture and laboratory course concurrently for general chemistry 167 and 167L. Participation for think aloud interviews was announced equally well in all the four courses of Chemistry 167, 167L, 177 and 177L, yet only two students from Chemistry 167 and 167L participated in interviews which resulted in 18 students from the lecture only portion and 22 students for both concurrent laboratory and lecture portion that included students from 177, 177L, 167 and 167L combined.

These studies also lack an investigation of differences between the males and females attitudes, formal-thinking and problem solving due to a smaller number of females participating in the study for Chemistry 167 and Chemistry 167 laboratories which reduced any chances of comparing the male participants with the female participants.

Further Studies

For further studies it may be worthwhile to conduct focus group interviews of students taking only the lecture course in general chemistry and students taking concurrent lecture and laboratory course. In addition, correlations between student problem-solving and laboratory exams scores may be studied to gather additional evidence on problem solving and the impact of laboratory instruction.

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CHAPTER 3

IMPLEMENTING STUDENT ROLES IN GENERAL CHEMISTRY LABORATORY: STUDENT-LED INSTRUCTOR FACILITATED GUIDED-INQUIRY BASED LABORATORY (SLIFGIL)

Abstract

The present study is about the Student-Led Instructor Facilitated Guided-Inquiry Laboratory (SLIFGIL) approach. Previous researchers demonstrated that students instructed using the Science Writing Heuristic (SWH) approach which is a type of guided-inquiry based laboratory instruction, performed academically better than the students receiving the non-SWH or the traditional laboratory instruction. In the present study the practice of the SWH approach is extended further, with the students leading the laboratory session in facilitation with their laboratory instructor. Students are assigned various roles that are consistent with the laboratory format for the SWH approach such as beginning question expert, safety expert, data table expert, claims expert and evidence and analysis expert.

Implementation of student roles in accordance with the SWH approach necessitates a learner-centered classroom environment and accountability on the part of the students. Students tend to own their ideas and construct their learning in such a classroom dynamic where they work along with the instructor and their peers to support each other in their knowledge construction and transfer. This study was based on mixed-methods research design. The quantitative component of the study includes results from the American Chemical Society's California diagnostic test, instructor generated general chemistry hour exams administered during the semester, the American Chemical Society's first semester

general chemistry exam administered as the end of semester final exam, and the laboratory practical exams administered for the laboratory component of the course. The qualitative part of the study involved student observations at the beginning and end of semester, analysis and coding of student laboratory reports and student videos at the beginning and the end of the semester.

The results of the study indicate that the students who were involved in the group roles consistent with the teaching approach performed better on the hour exams and laboratory practical exams as compared to students in SWH approach labs that were solely instructor facilitated. Among students in the SLIFGIL group approach there was an increased amount of interaction among students and a higher level of student preparedness and understanding of the SWH format. Further, student writing improved as a result of undertaking student roles.

Introduction

One would imagine that students would come prepared to the laboratory and that the instructors would know what to teach and how to teach effectively. This would be the model of an ideal student and an ideal instructor. In reality only a few students do the preparation needed for a laboratory and only a few instructors are equipped with adequate content knowledge and effective teaching skills. Irrespective of the best teaching methods being employed, there are always a few students who do not care about their learning and a few instructors who have good intentions but are unaware of means of engaging students and making them accountable during laboratory sessions. So what happens when students do not interact as much as the instruction format requires the students to interact? What can be done when students do not come prepared with the pre-laboratory component of the Science Writing Heuristic to ensure that laboratory is conducted smoothly with students doing the work that is required to construct conceptual understanding along with laboratory skills? Is there a way that instructors can involve students in their knowledge construction by making them accountable for learning in the laboratory, contributing to group work, and understanding the process of the Science Writing Heuristic by actually living it as an experience and not only using it for writing laboratory reports?

The purpose is to better understand the effects of Student-Led Instructor Facilitated Guided-Inquiry based laboratories as a treatment for two laboratory sections in general chemistry. The concurrent mixed-methods study (Creswell, 2008) uses both quantitative data and qualitative data. Students' performance on the American Chemical Society California Diagnostic, the American Chemical Society one semester general chemistry exam, test scores on problems from the four hour exams, laboratory practical exam scores, and laboratory report scores were used to assess student performance and chemistry content knowledge. Qualitative interviews of students and video-tapes taken at the beginning and end of the laboratory course were also analyzed along with their laboratory reports.

Theoretical Framework

"Theory is extremely useful because your theory determines what you can see."- Albert Einstein.

In a setting like a chemistry laboratory, several factors influence the acquisition of chemistry content knowledge. These include students' prior knowledge and experience with the laboratory; materials and methods employed; student interaction with peers and instructor during the laboratory class; and the presentation of laboratory work in the form of laboratory reports.

Assumptions from constructivism, symbolic interactionism and writing to learn science form the theory base for this study. From a constructivist standpoint, knowledge is constructed in the mind of the learner (Bodner, 1986). Learners build their own understanding as opposed to the traditionalist view of knowledge in which the learners construct replicas of reality or seek to match the truth with reality. Constructivism emphasizes the role of the individual in the construction of knowledge. Constructivist learners search for meaning and look for patterns in events instead of regurgitating information. Knowledge construction is thus seen as a search for fit and not a match with reality as no two individuals can have exactly the same understanding for an event (Von Glasersfeld, 1984). Bodner (1986) further reasons that knowledge construction is an undertaking of an individual mind yet groups of people can share common knowledge considering that the process of knowledge construction requires simultaneous testing of knowledge. Individual knowledge must be viable; it must work and be useful. For epistemological considerations, *constructivism* focuses on the meaning-making activity of the individual mind and the term *constructionism* is used where the focus includes the collective generation [and transmission] of meaning (Crotty, 1998). Personal (radical) constructivism focuses on the individual knower and the acts of cognition and social constructivism focuses on how the social interactions of the members of a group lead to an understanding of specific life circumstances. Radical and social constructivism emerge at opposite ends of a continuum.

Learning is a complex process occurring within a social context, but it is ultimately the individual who does the learning. *Useful knowledge therefore cannot be transferred intact from the mind of the instructor to the mind of the learner. It is thus important that any constructed knowledge appropriately functions in the context in which it arises* (Bodner, 2001). Each of us has a unique way of making sense of the world, but from a social constructivist view, our culture shapes our world view and perception of things. Outside the classroom, most people learn and work collaboratively and not individually as they are asked to do in a classroom setting (Resnick, 1988). Thus, learning in any place may be facilitated through collaborative social interaction for social construction of knowledge. According to Crotty (1986),

> "While human beings may be described in a constructivist spirit as engaging in their world and making sense of it, such a description is misleading if it is not set in a genuinely historical and social perspective. …….. We are all born in a world of meaning. We enter a social milieu in which a system of intelligibility prevails. …Constructivism embraces a whole gamut of meaningful reality. All reality as a meaningful reality is socially constructed."

Thus the constructive model of instruction necessitates a paradigm shift in the classroom as physical or logico-mathematical knowledge cannot be transferred intact from the mind of the instructor to the mind of the students by direct instruction. However the instructor can act as a facilitator and teach by negotiation instead of teaching by imposition (Bodner, 1986). The traditional model of instruction poses barriers for learners when they are offered precise, well-defined problems that require formal definitions and symbol manipulation. Such a format of instruction depletes student's general abilities of intuitive reasoning, problem solving and meaning negotiations, all of which are important stages of knowledge construction. Knowledge should not be imparted as a finished product for the end user but rather seen as an active and evolving effort on the part of the learner in the process of making sense of the world (Gurney, 1989)

People consciously or unconsciously adopt the behavior and belief systems of the social groups of which they are a part. While the activities of a group are shaped by its culture, the meaning of these activities and purpose is socially constructed through the negotiations among the members of the group (Brown, Collins, and Duguid, 1989). The world of a symbolic interactionist is a peaceable and growthful world consisting of intersubjectivity, interaction, community and communication. Three assumptions of symbolic interactionism are (Blumer, 1969):

1. Human beings act toward things based on the meanings that these things have for them.
2. The meanings of such things are derived from and arise out of the social interaction that one has with the peers.
3. These meanings are handled in and modified through an interpretative process used by the person in dealing with the things he encounters.

Pragmatism enters sociology in the form of symbolic interactionism (Mead, 1962; Maines 1997). According to symbolic interaction theory, people live in an environment that is natural and symbolic. As a process, symbolic interaction is invigorated by mutual meaning and merit when aided by mental symbols. Objects do not have any inherent meanings. Meanings are attributed to objects as a result of reciprocal interactions among individuals. Symbolic interactionists thus claim that facts are based on and directed by symbols as a result of experiences. Language provides meaning to human experiences and behavior by means of symbols that form the basis of communication and bring in a different perspective within a group of people (Aksan, Kisac, Aydin, and Demirbuken, 2008). Methodologically, the investigator applying symbolic interactionism as a theoretical construct presents the standpoint of those studied as it centers on human communication and its consequences (Maines, 1997; Denzin, and Lincoln, 1998). It is possible only because of the significant symbols, that is, the language and other symbolic tools that we humans share, and through which we communicate. Through dialogue, we can become aware of the perceptions, feelings and attitudes of others and interpret their meanings and intent. The perceptions resulting from actions are characteristic to both learning and activity; how a learner perceives an activity may depend on the tools available and the appropriated use of the activity in a laboratory. What learners perceive determines how they act and learn (Brown et. al, 1989). As argued by Brown and researchers from the situated cognition standpoint, activity plays a central role in learning as it leads to indexicalized representations that are not equivalent or universal among learners. However, from a symbolic interactionist view, an activity may be deemed meaningful when it is interpreted by the learner based on their thought processes and interactions with the social group. The central idea of symbolic interactionism is to put oneself in the place of others and see from others' perspectives (Kuhn, 1964; Crotty, 1986).

Literature Review

In a review study on the role of laboratory, Hofstein and Lunetta (1982) emphasize creating a healthy laboratory environment as an important goal for many contemporary science educators. The study indicates a need to research what is actually happening in the laboratory indicating a need for objective information about the interactions between teachers, curriculum resources, and students and about teacher and student behaviors during a laboratory-based learning sequence. The vast differences in the learning strategy from one type of laboratory to another are bound to affect learning outcomes. More research needs to be done to analyze the differences in learning outcomes due to different instructional strategies. The differences among various activities in the laboratories, the influence of interaction, style of laboratory, prior learning and students' development of logic need further research.

Four different styles of laboratory instruction include expository instruction, inquiry – based instruction, discovery (guided-inquiry based) instruction and problem-based instruction (Domin, 1999). Expository instruction commonly referred to as traditional or verification style, is widely used in college chemistry laboratory instruction yet it is widely criticized due to its limited role in student learning. The very design of expository instruction demands minimal effort from the instructor, offers little challenge to students' thinking skills, promotes rote learning, and is a grim portrayal of scientific experimentation. Inquiry-based activities on the other hand, are inductive, require the students to generate their own procedure and have no pre-determined outcome (Hofstein, 2004).

Compared to a traditional format students in inquiry-based laboratories are involved, receive less direction from the instructor, and bear more responsibility for designing the procedure to answer the questions they formulate. Discovery based laboratory instruction lies on the continuum where traditional teaching is at one end and inquiry-based teaching is at the other end. The discovery-based approach differs from the inquiry-based approach in its guided nature. In this inductive approach, students formulate their own question for investigation, but the instructor guides the students to the desired outcome. The instructor is thus aware of the outcome and students follow a procedure to answer their question or to discover concepts by experimentation. The procedure is not cookbook in nature, as students have some degree of freedom in deciding their question and they make a choice from the available experimentation materials to answer their question.

Brown et al. (1989) emphasize the role of authentic activities which are coherent, meaningful and purposeful for learners as many activities in traditional laboratories do not represent the undertakings of science practitioners; this limits students' abilities to structure their understandings and supporting cues that arise from the context. According to Bodner (1986), anyone who has studied chemistry or tried to teach it to others knows that active students learn more than passive students. He further suggests that chemists should have a more natural affinity for a model that promotes active learning of chemistry. One such model of teaching that promotes active learning in laboratories is the Science Writing Heuristic approach.

Science laboratories are valued by academic scientists as they believe that laboratory-based instruction plays a central role in students' learning and development of study skills. Various external factors facilitate success in the science laboratory including the curriculum, resources used (laboratory manual, computer, equipment), the learning environment, and teaching effectiveness. Of all these factors, the learning environment has a significant impact in shaping student experiences. Altering the learning environment may lead to improved performance of students in both the lecture and laboratory components of the course. The learning environment (external influences that interact with the learner during the learning process) is as important as the characteristics of the individual learner (Domin, 1999).

Students in cooperative learning groups perform better as compared to students in the laboratories focusing on individual work. The effectiveness of laboratories in fulfilling the goal of meaningful learning and development of reasoning skills depends on the nature of the exercises and investigations, the way in which the students interact with one another, the instructor, the role played by the pre-laboratory, and the post-laboratory discussions (Lazarowitz and Tamir, 1997;).

As an inquiry approach to teaching and learning, the Science Writing Heuristic approach captures elements of a learning cycle approach, group work, guided-inquiry and writing-to-learn-science teaching strategies and promotes learning of chemistry using laboratory (Burke, and Greenbowe, 2006).

The Science Writing Heuristic approach can be understood as an alternative format that students use for their laboratory reports and a teaching technique used by the instructor to aid the flow of activities associated with an experiment. A heuristic is a guide or a method used to help individuals/groups to discover or reveal a principle/concept. As compared to traditional laboratories, in the SWH approach, the instructor assumes the role of a facilitator who helps guide students in experimental design and to answer their questions by investigations. Students thereby develop conceptual understanding of the phenomenon and learn useful skills (Greenbowe & Hand, 2005).

Rudd, Greenbowe and Hand (2002) explored the effectiveness of the SWH approach with students enrolled in a first-year chemistry course for science majors. Students in one of the laboratory sections used the SWH format and students in a control group used a traditional laboratory format. The results of the study indicate that students using the SWH approach were more engaged and produced claims and evidence that better connected the observations to the experiment. Prolonged exposure to the SWH approach promoted active student learning and meaningful learning through writing and discussion. In another study, Rudd and Greenbowe (2002) compared the performance on lecture exams and laboratory practical exam of students using the SWH approach versus students using a standard laboratory curriculum. The results of the study indicate that SWH students exhibited better understanding of chemical equilibrium, displayed better learning gains, and performed statistically significantly better when explaining concepts.

Poock and Greenbowe (2007) conducted additional studies on the effects of the SWH approach on student performance in a general chemistry laboratory facilitated by graduate teaching assistants. The study rated the degree of implementation of the SWH approach including inquiry, group work and report writing in a two-semester general chemistry sequence. The results of the study indicate higher academic performance and a better grasp of concepts among sections with high TA implementation and high student acceptance of the SWH approach.

Schroeder (2007) studied the carry-over effect for students in a traditional laboratory who had used the SWH approach in a previous general chemistry laboratory. The analysis of student performance on course exams revealed a better performance by students who had previously used the SWH approach on reaction mechanism problems and comprehensive overall final examination compared to those who had not.

Student-centered or inquiry-based instructional approaches have made a difference in improving student engagement and understanding of chemistry. These strategies, though different in style have common goals, in the sense that they are not monotonous as one-way lectures tend to be. They emphasize continual interaction between students and instructor to ensure a better grasp of the materials by the students. The progressive curriculum emphasizes student teams working in groups and encourages students to apply scientific principles and reasoning to real world situations (Brainard, 2007).

The traditional approach is teacher-centered with the teacher playing the central role of the “academic” and making all decisions regarding the laboratory activities and students learning. In the alternative student-centered approach to learning, the instructor takes the role of guide, coach, motivator, facilitator, and coordinator of learning processes and resources. A student-centered approach is based on a context of learning that promotes active engagement of students in the subject matter, making a student an active participant in the learning process by analyzing, asking questions, using judgment, combining ideas and processing information for problem identification and problem solving.

In a study at Mississippi State University, a design of the student-centered laboratories required the students to make a choice of topics. Lab captains were selected for topics of personal interest in chemistry to ensure the effective design and completion of the laboratory exercise. Each team of Lab Captains were responsible for design, setup, instruction, monitoring, and data compilation, development of handouts, making reagents, developing a solution (rubric) for the lab and providing it to the instructor for grading the lab reports. The results of the study indicated an increase in student learning and an enhancement of the laboratory experience when students designed experiments for other students. Students felt immersed in the process of experimental design and analysis with a team of peers (Traux, 2007).

Student teamwork enhances features of lab work such as cooperative learning and social interaction. Students pairs work together on an activity and at the same time create an environment involving each student intimately with the task. In a study at Babson College, each pair of students submitted one lab report for the experiment and they received the same grades. An individual laboratory exam was used to maximize student involvement and accountability, making the students more actively involved and attentive in the laboratory. To foster a collective group sense the class collated and analyzed the data from the student teams. The results of the study indicated that students liked to work together, and collaborative learning was enhanced when students worked in pairs (Adams, 1998; Blosser, 1993).

The four fundamental ideas of cooperative learning are (i) positive interdependence among the students, (ii) face-to-face interaction among the students, (iii) individual accountability for learning, and (iv) application of small group skills and interpersonal skills among diverse students. Effective implementation of cooperative learning requires specification of instructional objectives; grouping students appropriately for learning; being explicit to students about the academic tasks and the cooperative methods employed for accomplishing these tasks; monitoring group progress; intervening to provide assistance when necessary; and evaluating student progress with student input (Johnson & Johnson, 1984; Cooper, 1995).

Cooperative learning has been introduced in different formats by several researchers. Some of variations of cooperative learning are jigsaw (Aronson, 1978), jigsaw II (Slavin, 1988), jigsaw III (Kagan, 1989), student teams-achievement divisions (STAD) (Slavin, 1988) and group investigations (Sharan et. al., 1989). In case studies on the application of cooperative learning methods (the jigsaw method and application of competence levels of students with each group having high-level and low-level students) in chemistry classroom at university level, findings indicate that students develop self-confidence, demonstrate cooperation and motivation by sharing their ideas, and become more participative. Learners in partnership and collaboration with others achieve a fuller and a broader understanding of the qualities and the values of citizenship (Barbosa, 2004).

A review study on the quality of research on cooperative learning at the secondary level indicates the use of cooperative learning methods previously listed above (Newmann, and Thomson, 1987). The review study emphasizes that more research is required on the application of cooperative learning with secondary students. Researchers should investigate interaction of method, level of thought, student background characteristics, and student status within the group. Research needs to be done to examine the specific types of verbal interactions within the groups that are most likely to boost achievement.

In a review study Lunetta, Hofstein and Clough (2007) suggest that there are substantive differences in laboratory settings among different cultural and classroom contexts. Hence it is necessary that science education researchers carefully make explicit detailed descriptions of the participating students, teachers, and classrooms as well as curriculum contexts with emphasis on learning objectives; the nature of instructions provided by the instructor and the laboratory guide; materials and equipments available for use; nature of activities and student-student; teacher-student interactions during laboratory work; numbers and roles of students in each laboratory team, and finally, format of student laboratory reports.

Scope and Intent of this Study

Okebukola (1986) states that research on the examination of factors that can lead to favorable attitudes towards the chemistry laboratory should be undertaken and the knowledge of the process of structuring the student interactions during the laboratory may improve their attitudes towards their chemistry laboratory projects.

The Science Writing Heuristic approach has been proven to show significant learning gains for students at school level and for college level chemistry courses. Yet the approach has some limitations that hold it from operating at a level of including students' participation as it should. Effectiveness of the Science Writing Heuristic approach depends on the level of preparation that the graduate teaching assistants receive and the level of implementation and acceptance by the students for the approach (Rudd, Greenbowe, and Hand, 2001; Burke, Hand, Poock, and Greenbowe, 2005; Poock, Burke, Greenbowe, and Hand, 2007). First, graduate teaching assistants may not be much inclined to use an inquiry-based approach for teaching viewing the newer teaching method to require more teaching and grading as compared to a traditional method of instruction. A second limitation is the length of time it takes for students to comprehend the format and use it fruitfully as learners. A third limitation is the pre-laboratory preparation that the Science Writing Heuristic approach requires from students. While some students display a proactive approach to learning, a fairly large number of students believe during the first few weeks of the laboratory course that it is the responsibility of their teaching assistants or instructor to exactly tell them what to do or which data needs to be collected, and which observations need to be made. Students sometimes end up rejecting the newer teaching method and block their minds to any expectations their instructor outlines for preparation of laboratory. This affects the student contribution and lowers student participation in the activity. An expert instructor is aware of strategies to enable students to share their thinking, challenges student misconceptions by carefully designing learning activities, and scaffolds students' understanding by carefully questioning students throughout the course of learning (Clough, 2002). Yet the pressing issue is learning is impacted at institutions wherein the students in undergraduate chemistry laboratories are facilitated by teaching assistants who receive cursory training at the beginning of their TA career and may have no knowledge of effective pedagogy besides a few stints at training sessions. Lack of training of the instructor makes it difficult to implement the Science Writing Heuristic approach in its true spirit as an active learning approach. A poorly implemented Science Writing Heuristic approach based laboratory is thus very much similar to the verification laboratories as the graduate teaching assistants resort to telling everything to their students in the pre-laboratory discussion session. Students in such an environment don't receive the training they should for optimal learning using the Science Writing Heuristic approach.

In this study student-roles were implemented to minimize instructor directness and make the Science Writing Heuristic approach more student-centered and engaging for students. Student are assigned various roles that are consistent with the laboratory format for the SWH approach such as beginning question expert, safety expert, data table expert, claims expert and evidence and analysis expert. Student role assignment was done to ensure that: (a) students own their learning; (b) come prepared with ideas and questions for the experiments and, (c) respect each other as members of collaborative learning groups. Prior studies have indicated that a greater degree of participation of students in the laboratory work may lead to a more positive attitude of students towards the laboratory. Students' perception of one another and their interactions with one another are neglected aspects of instruction. Cooperation should be the dominant interaction pattern in the classroom. In a situation where teachers perceive widely differencing interaction patterns among students, should change their approach to instruction. Teachers' guidance of students with one another will influence the way students learn, the attitudes they will form about the subject matter and the instruction and will shape the perceptions of the students for the subject and other people who contribute to their knowledge construction(Johnson, and Johnson, 1985).

Research Questions and Hypotheses

The following research questions were investigated:

1) Do the students of Student-Led Instructor Facilitated Guided-Inquiry Laboratories (SLIFGIL) perform better on exams than the students in instructor facilitated Science Writing Heuristic based laboratories?

2) Do the students in the students-led, instructor facilitated guided inquiry laboratories write higher quality laboratory reports as compared to the students in instructor-facilitated laboratories?

It is hypothesized that there is a significant difference between the means of the students (on hour exams, ACS first semester general chemistry exam, and the laboratory practical exam) using the SLIFGIL instructional approach and the means of the students instructed using the instructor facilitated SWH approach.

The research hypothesis is stated as follows:

$$H_0: \mu_{\text{SLIFGIL Science \& engineering majors}} = \mu_{\text{SWH-science \& engineering majors and chemistry majors}}$$

$$H_A: \mu_{\text{SLIFGIL Science \& engineering majors}} \neq \mu_{\text{SWH-science \& engineering majors and chemistry majors}}$$

It is further hypothesized that there are no differences in the quality of the laboratory report component for students instructed using SLIFGIL as compared to students instructed by instructor facilitated SWH approach.

Experimental Design

Class Assignment for the study

The study involved students enrolled during the fall term in a first semester of a general chemistry sequence for science and engineering majors at a midwestern university. Six laboratory sections were selected for the study and four teaching assistants were assigned to instruct these six laboratory sections. Two teaching assistants in the study were each assigned to a laboratory section in which the students received the standard instructor facilitated Science Writing Heuristic approach instruction and another section in which student roles were implemented (SLIFGIL). Two different TAs were assigned to teach two separate honors students (chemistry majors) laboratory sections using standard instructor facilitated SWH instruction. Thus there are three groups in the study- one group is the students who are science and engineering majors and are instructed using the Science Writing Heuristic based instruction, the second group is chemistry majors (honors students) receiving Science Writing Heuristic based instruction, and the third group is science and engineering majors receiving SLIFGIL based instruction (student roles).

Modified Science Writing Heuristic approach incorporating student roles, aka Student-Led Instructor Facilitated Guided-Inquiry Learning (SLIFGIL)

The Science Writing Heuristic (SWH) approach to teaching applies the principles of guided-inquiry and a learning cycle approach to teaching. The SWH based laboratories differ from the traditional verification/cookbook laboratories fundamentally in the laboratory environment and laboratory report format. As opposed to traditional laboratories in which the students work individually and follow a step-by-step procedure for verification of concepts/principles, SWH laboratories require students to propose a question for investigation (on topics from their lab manual), design a procedure with guidance to answer their question, and establish the safety measures required for the activity. Students work in groups and they tabulate data on the chalkboard and on an excel spreadsheet on the computer. The instructor facilitates the pre-laboratory discussion encouraging students to write their group beginning questions on the chalkboard. After a brief discussion of procedure and safety by the instructor, students work in their groups and collect the data. The instructor circulates in the laboratory asking questions of students that help students make connections to the concepts they are trying to construct. The instructor facilitates student learning by asking a question in response to students' questions and not giving away an answer directly. When sufficient observations are made and data is collected students summarize their group data on the chalkboard. The instructor facilitates a post-lab discussion to help students construct the concepts and relate to what the students have/will learn during class.

In the present study, the SWH approach is modified to understand the effects of assigning class members responsibility of leading laboratory discussion about targeted topics and assisting the instructor to conduct the laboratory effectively. This method was implemented in two lab sections during the general chemistry 177L course at Iowa State University (N=32). The study was further carried out in the second semester general chemistry course to study the carry-over effects of implementing student roles in a Science Writing Heuristic based laboratory to answer the research question- (a) does the implementation of student-led instructor facilitated laboratories produce a change in the students quality of laboratory reports (indicating increased student understanding of concepts). b) Does the implementation of student-led laboratories lead to a better student performance on post-tests for specific concepts?

Members of these student-led instructor facilitated guided-inquiry learning based laboratories are assigned the groups designated by letters of the alphabet (A, B, C, D and E) with five students per group. Students wear their nametags in the laboratory with their group alphabet designation. Each laboratory session opens with the students of each group leading different laboratory components. Roles are assigned to students beginning of lab period. Students get the role assignment each week when they meet in the laboratory and are not provided any information about which group will lead the laboratory on a given week. The roles consist of Beginning Question expert, Safety expert, Procedure expert, Data Table expert and claims and evidence expert. As the laboratory session begins the instructor may call forward all the students in group A. The students of the selected group are provided with role-cards to choose their role (for example, who wants to be the Beginning Question expert from the selected group). Once students take their roles they are the experts for that particular component of the SWH format. The Beginning question expert helps the students in the class to get in their groups and discuss the beginning question individual student have. The Beginning question leader thus facilitates the class students to discuss and write their beginning questions as a pair on the chalkboard. The experts also discuss their own questions while they lead the class. Each pair of student in the class is encouraged to contribute at least one beginning question. The Beginning question expert then engages the entire class to select one class beginning question and identify the variables to be explored. The groups thus discuss with each other and propose the question they believe is worthy of answering by experimentation. The students decide the variables such as the mass range or the reagents they will be using from a list of chemicals available in their laboratory manual and on the reagent bench and divide the work among the group members.

Safety expert discusses issues of safety and waste disposal for the laboratory and is in charge of all safety matters for the day. The Procedure expert draws students' attention to the steps that will help them complete their group investigations by asking questions. Instead of outlining the procedure for the students, the procedure expert is encouraged to ask questions from the groups to get them to draft a procedure. The instructor facilitates the discussion in between if something needs to be added. Overall, the experts lead the lab and they are responsible along with the instructor to assist students for all student queries related to their assigned roles. The Data Table expert discusses calculations and the data table layout with the students and makes sure that every group enters the data on the chalkboard and in the

Excel spreadsheet. The Claims and Evidence expert leads the post-lab discussion along with the instructor by asking student groups to make claims supporting it with the evidence from their data, observations and class data. The instructor mainly facilitates the end of lab discussion on reflection for the activity and connecting the concepts and encourages the student leaders to account for their observations and their experience with leading the laboratory. Different groups lead each laboratory activity and when the groups get a chance to lead the laboratory again, the roles are assigned to different students to ascertain that the same role is not repeated with the same individual in a certain group.

Data Collection

Data collection was done in phases. Quantitative data was collected via student scores on hour exams, laboratory practical exam and the first semester general chemistry ACS final exam collected during the course of the semester. In addition copies of specific exam problems were made from the student hour exams about topic of stoichiometry, thermochemistry and gas laws. These copies of exam problems were made for the students in the honors sections, SLIFGIL sections and SWH sections of the course. From time scale perspective a unit on stoichiometry is covered early on in the semester and students are tested on it via the first or the second hour exam. Thermochemistry is covered closer of mid-semester and students are tested by third hour exam. The topic of gas laws is covered by the end of the semester and is on the fourth hour exam. Laboratory activities are consistent with the lecture syllabus and the units being covered during the class. So, a laboratory may be the first place wherein students get to uncover or explore the concepts before being introduced to the topic during the lecture. Data collection was thus done keeping in view the topics that were covered in both the lecture and the laboratory component of the general chemistry curriculum. Copies of ungraded student laboratory reports were collected. In addition, laboratory notebooks for the students from laboratory sections for the treatment and the control groups were collected. Contents of student laboratory notebooks were then typed in the MS-Word program rich text format and transferred later to ATLAS.ti program for coding and analysis.

Laboratory sessions were videotaped twice, once at the beginning and then at the end of the semester to compare student progress across the semester along with the observation notes throughout the semester during different laboratory activities. Students from both the SWH-based laboratories and SLIFGIL-based laboratories were videotaped on a three hour activity for a stoichiometry-based laboratory. The videography was done for student groups in the laboratories by a videographer instructed to capture student discussions within groups and with the instructor. The camcorder was equipped with remote sensing microphone and there were two camcorders operating per session.

Video recordings were completely transcribed in MS-Word and transferred to the ATLAS.ti program for analyses. Qualitative data was used to characterize the interaction dynamics of a SLIFGIL-based laboratory and comparing SLIFGIL laboratory session to SWH-based laboratory in which the instructor was the sole facilitator. The entire video recordings for the three hour laboratory session were coded for the interaction patterns and comparison of SWH and SLIFGIL laboratories.

Five students were individually interviewed from SLIFGIL-based laboratories. The students from both the SWH-and SLIGIL-based laboratories were invited to be interviewed during an announcement to the laboratory sections participating only in the study, but only the students in the SLIGIL-based laboratory signed up for the interviews. Five students from the SLIFGIL-based laboratory participated in these interviews. The interviews were structured and intended to derive information on the implementation of group roles and student opinion on the impact of group roles on student engagement and learning in laboratory.

Data Analysis

The students in the student-led instructor facilitated guided-inquiry laboratories were compared to students in the Science Writing Heuristic based laboratories that were solely facilitated by the instructor. Assessment of the prior chemistry knowledge of students in the treatment and control laboratory groups was done for a baseline comparison using their scores on the American Chemical Society, California Diagnostic Test. The California Diagnostic Test instrument was developed to assess the knowledge, skills and ability students need for a general chemistry course and it provides an assessment of students' knowledge of high school chemistry as well as basic math skills (Russell, 1994). Results for the quantitative portion of the study were analyzed using a t-test (at $\alpha=0.05$) for the difference of means between the two groups and the Analysis of Variance (ANOVA) for the three independent groups (SLIFGIL, SWH and SWH-Honors).

The purpose of the qualitative data analysis was to compare students' laboratory report quality, and assess the differences in SWH and SLIFGIL based laboratory sessions as well as compare the number of student-student and student-instructor interaction in SLIFGIL laboratory and SWH laboratories. An additional hypothesis was proposed: the implementation of student roles (SLIFGIL) in the laboratory has an impact on student-student interactions and student-instructor interactions. Student written reports were analyzed based on a rubric developed by Choi, Hand, and Yager on the quality of scientific argumentation of students (2008). Choi, Hand, and Yager (2008) investigated the quality of argument found in student science writing by developing an analytical and holistic framework for SWH-based laboratory reports. Qualitative video data was analyzed for the interaction patterns between the students, students and the teaching assistant and student-groups and teaching assistant interaction. In addition, the qualitative data was also analyzed for differences between the conduct of SWH and SLFGIL based laboratories. The findings from qualitative analysis were integrated with the quantitative data to generate conclusions for the study. Students who participated in the study during the first semester general chemistry course were tracked for their performance in the second semester general chemistry sequence.

Results and Discussion

Quantitative Data

In this study two research questions were addressed. In order to answer the first research question about comparison of academic performance it is important to know whether there is any difference in the groups under study. For baseline comparison of students' prior knowledge at the beginning of the semester, the subjects were given the ACS California Diagnostic Test. Table 1 shows a comparison of student scores on the ACS California Diagnostic Test for students in three groups: the students in the SWH-group; the SWH-instructed honors students, and the SLIFGIL group.

Table 1: ACS-California Diagnostic pre-test for first semester general chemistry means and standard deviations.

	SWH	SWH-Honors	SLIFGIL
N	32	32	34
Mean (Std.dev.)	22.68 (3.92)	23.09 (6.32)	23.67 (5.24)
Major	Science and Engineering	Chemistry	Science and Engineering

The means and standard deviations for the ACS-California Diagnostic Test are given in Table 1 followed by one-way ANOVA comparisons for the three groups in Table 2.

Table 2: Summary of one-way ANOVA for ACS California-Diagnostic (pre-test).

Source	SS	DF	MS	F	Prob>F
Groups	73.45	2	36.72	1.33	0.26
Error	2623.09	95	27.61		
Total	2696.48	97			

Based on the mean values and one-way ANOVA test there are no significant differences among the three groups at the beginning of the first semester general chemistry course. The mean, $\bar{x}$ and the standard deviation, s (or the variances s^2), are descriptive measures that together provide useful information about the distribution of an observed set of values. The sample variance s, for n observed values with the mean $\bar{x}$, though not presented in the tables are simply the sum of the squared standard deviation divided by (n-1). For a normal bell-shaped distribution, the interval follows an empirical rule such that:

a) The interval ($\bar{x} \pm s$) contains approximately 68% of the observations.

b) The interval $\bar{x} \pm 2s$ contains 95% of the observations

c) The interval $\bar{x} \pm 3s$ contains all of the observations.

In each of the intervals mentioned above, the mean explains the location and the standard-deviation indicates the dispersion of the given part of the data. Thus for n=32 for

SWH group, the $\bar{x}$ =22.68 and standard deviation is 3.92. Thus a) $\bar{x}$ ±s, for SWH group 22.68±3.92, indicates the interval 18.76 to 26.6 and thus should include (0.68)(32)=21.76 observations; for the SWH-Honors students group $\bar{x}$ =23.09 ±6.32 gives the range 16.77 to 29.41and (0.68)(32)=21.76 observations; for the SLIFGIL group $\bar{x}$ =23.67 ±5.24 gives the range 18.43-28.91 and (0.68)(34)= 23.12 observations. With respect to the calculations for the $\bar{x}$ ±2s the range for the SWH group is 14.84-30.52 with (0.95) (32)=30.4 observations; for the SWH-Honors group the range is 10.45-35.73, which indicates (0.95)(32) =35.73 observations; the range for the SLIFGIL group is 13.19-34.17 and includes 32.3 observations. In case of $\bar{x}$ ±3s the interval range for the SWH group is 10.92-34.44 and includes all the observations; the SWH-Honors group has an interval range of 4.13-42.05; and the SLIFGIL group has an interval range of 7.95-39.59 and includes all the observations as well. The mean values of the three groups are fairly close. Since 95% of the observations for SWH, SWH-Honors and SLIFGIL groups fall within two standard deviations of the mean in either direction; the range of the data for each group is close to four standard deviations enabling estimation of the standard deviation by computing the range for the student scores on the ACS California Diagnostic Test. The estimated standard deviation for SWH group is found to be 4.0 which is close to 3.92 ((30-14) 4=4); the SLIFGIL group has an estimated standard deviation 5.25 ((36-15)/4=5.25) and the SWH-Honors group has an estimated standard deviation of 6.25 ((36-11)/4=6.25). This indicates that the distribution is normal in each of the groups as the intervals computed for each group follow the empirical rules outlined above. Note that estimating of the standard deviation by using the range of observations is not a very conservative method. A better approach for computing the estimate of the standard deviations is Tchebysheff's theorem according to which "for any arbitrary constant k, the interval ($\bar{x}$ $\pm ks$) includes a proportion of the values of at least [1-(1/k^2)]. The strength of the Tchebysheff's theorem is that it applies to distribution of any shape and is more theoretical in nature. Using Tchebysheff's theorem it is found that for the SWH group, 30 out of 32 observations fall in the range 14.84-30.82 which equals 0.9375 of the values; for the SWH-Honors group 31 out of 32 observations fall in the range of 10.45-35.73 which gives a proportion of 0.96875 and for the SLIFGIL group the proportion is 0.9411 as 32 out of 34 observations fall in the range of 13.19-34.17.

A one-way ANOVA is done to find the differences among the means of the California-Diagnostic Test for the three groups in the study (Table 2). It is important to understand whether the groups started out differently or they had a similar set of chemistry and math skills at the beginning of the semester. The one-way ANOVA procedure is used to determine whether there are significant differences among the means when there are more than two groups.

In an ANOVA, the test-statistic computed is called the F-ratio or F-test or Fischer's test. Thus a one-way ANOVA is simply another form of t-test for independent samples and is used to compare two or more means simultaneously (Ravid, 2011). The statistics for the ACS-California Diagnostic Test is displayed in Table -2 for one-way ANOVA. The F-ratio is not significant at $p<0.05$ level. A post-hoc comparison of the means is done to do pairwise comparisons of the means for the three groups using Tukey's method for multiple comparisons (also known as honestly significant difference HSD). By pair wise analysis it is found that the SWH, SWH-Honors and SLIFGIL groups have no statistical difference with p-value being 0.26 at (α=0.05).

Student participants in the first semester of general chemistry were given four hour-exams worth 100 points each and an end of semester final exam. The final exam was the American Chemical Society's one-semester general chemistry test with 70 questions worth 150 points.

As seen from Table 3, students in the SLIFGIL group have higher means as compared to the students who are in the Honors group and the SWH group. One-way ANOVA tests establish significant differences between the groups on ACS General Chemistry Test with an F-ratio=4.11and Prob.>F=0.0194. Similarly for the final laboratory practical examination, students in the SLIFGIL groups performed statistically significantly better than the students in the SWH and the SWH-Honors group with F-ratio=3.92 and Prob>F=0.023.

Table 3: Student performance in First Semester of general chemistry.

	SWH (N=32)		SWH HONORS (N=32)		SLIFGIL (N=34)	
	Mean	SD	Mean	SD	Mean	SD
Hour Exam 1	78.68	13.05	77.90	13.86	82.79	11.26
Hour Exam 2	78.65	12.96	77.75	18.20	82.5	15.50
Hour Exam 3	71.68	16.02	67.96	14.80	76.26	10.20
Hour Exam 4	79.12	11.51	77.18	13.25	81.85	11.85
ACS Final Exam (150 points)	100.23 (66.8%)	21.75	102.93 (68.6%)	23.37	114.37* (76.2%)	18.81
Laboratory Practical Exam (71 points)	50.40 (71%)	13.71	50.3 (70.8%)	13.8	58.00** (81.7%)	10.65

*F-ratio=4.11; Prob.>F=0.0194 ** F-ratio=3.92; Prob>F=0.023

Students were compared specifically for their performance on the second hour exam problem about stoichiometry. The problem on stoichiometry is a modified version of an end-of-chapter problem from the student text-book (Brown, Le-May, Burnsten, 2008). It involves the heating of magnesium metal in air leading to the formation of the metal oxide. Students are provided the mass of the metal and mass of the product and they are a) required to identify the change in the oxidation state of the metal; b) classify the reaction correctly as combination reaction and oxidation-reduction reaction; and finally c) calculate the percentage yield for the experiment given the data in the problem. Students solving this problem are expected to understand the concept of mole ratios in order to determine the numbers of moles of oxygen that combine with the given mass of magnesium as well understand the role of limiting reagent.

Stoichiometry problem on the second hour exam:

Q. After heating 1.078 grams of magnesium in air, 1.269 grams of an oxide of magnesium is obtained.

a. The initial oxidation state of magnesium is ----- and it changes to ------ (2 points). Write the balanced chemical equation (2 points).

b. Circle two terms that accurately describe this reaction (2 points).

Acid/base combination/synthesis decomposition double displacement oxidation-reduction single displacement.

c. What is the percent yield of this experiment? (4 points).

As seen in Table 4 students in the SLIFGIL group performed statistically significantly better than the students in the SWH group and Honors group with the F-ratio being 5.26 and Prob>F being 0.0068. Further analysis of errors in student work on this problem revealed issues with the concept of the oxidation state of the metal as +1 indicating the formula for the product to be Mg_2O and hence an incorrectly balanced equation and an incorrect theoretical yield. Students who solved this problem correctly identified the reaction as combination/synthesis and redox reaction and used stoichiometric proportions based on the correctly balanced chemical equation as shown below to calculate first the theoretical yield and then the percent yield of magnesium oxide.

$$2Mg(s) + O_2(g) \rightarrow 2MgO(s)$$

Table 4: One-way ANOVA for student-performance on stoichiometry problem.

Source	DF	Sum of Squares	Mean Square	F-ratio	Prob>F
Group (T,C or H)	2	72.35429	36.1771	5.2632	0.0068*
Error	95	652.99265	6.8736		
C. Total	97	725.34964			

Table 5: Summary of fit for one-way ANOVA stoichiometry problem.

R-square	0.099751
Adjusted R-square	0.080799
Root Mean Square Error	2.621756
Mean of response	6.081633
Observations (or sum weights)	98

The summary of fit report in Table 5 shows the R-square (also called coefficient of determination) and adjusted R-square. The R-square value is used to measure the proportion of variation accounted for by fitting means to each factor level. The remainder of the variation is thus attributed to random error. A value of 1 for R^2 indicates that fitting the group means accounts for all the variation and there is no error whereas when R^2 equals 0, the fit of the group means is as good as the prediction model as the overall response mean. The R^2 for a continuous model can be calculated using the equation:

Sum of Squares (Model)/ Sum of Squares (C Total)

The adjusted R^2 is a ratio of mean squares instead of the sum of squares and it can be calculated using the equation:

1-Mean Square (error)/ Mean Square (C Total)

Its role is to adjust the R^2 to make it more comparable with models having different numbers of parameters and it employs the degrees of freedom in its calculation. The R-square and adjusted R-square serve to explain the proportion in variation of y associated with the variable x. Based on the value of the R^2 and adjusted R^2 there is very little evidence of correlation between student performance on the stoichiometry problem and the instructional approach being used. A value of 1.0 for R^2 indicates high correlation whereas a value of 0 indicates no correlation.

Table 6: Means for one-way ANOVA stoichiometry problem.

Level	Number	Mean	Std. Error	Lower 95%	Upper 95%
C	32	5.68	0.46347	4.7674	6.6076
H	32	5.25	0.46347	4.3299	6.1701
T	34	7.23	0.44963	6.3427	8.1279

Note: C=instructor facilitated SWH; H=Honors students T= Treatment group SLIFGIL-based instruction

Table 6 shows the means and the standard error of the means for the Treatment, Control and the Honors group. The treatment group displays high mean of 7.23 as compared to the Honors group with a mean of 5.25 and Control group having a mean of 5.68. The two groups in which students took an active role in their learning thus showed improved performance as compared to chemistry honors. The standard error of the sample mean is obtained by dividing the sample standard deviation by the square root of the sample size. In the case of the stoichiometry problem, the experimental group has slightly higher standard error as compared to the SWH and the Honors-SWH students (Table 7).

Table 7: Means and standard deviations stoichiometry problem.

Level	Number	Mean	Std. Dev.	Std. Error Mean	Lower 95%	Upper 95%
C	32	5.68	3.08417	0.54521	4.5755	6.7995
H	32	5.25	2.68809	0.47519	4.2808	6.2192
T	34	7.23	2.01598	0.34574	6.5319	7.9387

When an ANOVA F-test is significant, the null hypothesis is rejected for similarity of means. In such a scenario multiple comparisons of means using post hoc tests are helpful to find the means that differ. Tukey's test is a one-step comparison of means that are significantly different from one another as it compares all the possible pairs of means. The Tukey test does pair-wise comparisons for the means of one treatment to the means of every other treatment. In case of unequal sample sizes, the test is conservative and finds when the difference between two means is larger than allowed by the standard error. The Tukey-Kramer post-hoc comparison of means indicates that the SLIFGIL and Honors-SWH groups are significantly different with p value=.0077 and the SLIFGIL groups are significantly different with p-value being 0.0481 at α=0.05 (Table 8). There is no difference between the Honors students who received SWH-based instruction and Science Majors receiving SWH-based instruction. This indicates that even though when student groups differ based on their majors, the overall instructional approach being same for the two categories of students lead to similar performance on the stoichiometry based problem (Table 9).

Table 8: Comparison of means between groups and confidence intervals

Level-Level	Difference	Std. Error Difference	Lower CL	Upper CL	P-value
T-H	1.985294	0.6457284	0.44780	3.522786	0.0077*
T-C	1.547794	0.6457284	0.01030	3.085286	0.0481*
C-H	0.437500	0.6554391	-1.12311	1.998114	0.7829

*α= 0.05; **q=2.38

Table 9: Abs(Dif)-HSD for the stoichiometry problem showing the levels and differences between the mean-pairs.

	T	C	H
T	-1.5140	0.0103	0.4478
C	0.0103	-1.5606	-1.1231
H	0.4478	-1.1231	-1.5606

Note: Positive values show pairs of means that are significantly different.

Level		Mean
T	A	7.23
C	B	5.68
H	B	5.25

Note: Levels not connected by the same letter are significantly different.

Table 10 displays student performance on the thermochemistry problem for the Honors group, the SWH students and SLIFGIL students. Students were given a modified end of chapter problem from their text and were asked to find the heat exchange for a reaction; solution and the enthalpy of the reaction in units of kJ/mole. The solution to this problem requires the student to understand the concept of the law of conservation of energy as well as understand the signs associated with the system and the surroundings in terms of what gains heat and what loses heat as a result of the chemical reaction (Greenbowe & Meltzer, 2003).

Thermochemistry problem on the third hour exam:

Q. When 150.0 mL of 0.100 M NaOH at 25°C is added to 150.0 mL of 0.100 M HCl at 25°C in a calorimeter, the temperature of the solution INCREASES to 59.2°C. Assuming that the specific heat of the solution is 4.18 J/gram °C, the density of the solution is 1.00 g/mL and the calorimeter absorbs a negligible amount of heat, complete the following:

a. Calculate $q_{solution}$ and $q_{reaction}$ for this system. Show all work for full credit.

b. Calculate $\Delta H_{reaction}$ in kilojoules per mole of HCl.

Table 10: One-way ANOVA for student-performance on the thermochemistry problem in first semester of general chemistry.

Source	DF	Sum of Squares	Mean Square	F-ratio	Prob>F
Group (T, C or H)	2	101.88971	50.9449	6.6653	0.0020*
Error	95	726.11029	7.6433		
C. Total	97	828.00			

Table 11: Related tables to one-way ANOVA on the thermochemistry problem in first semester general chemistry. Summary of fit.

R-square	0.123055
Adjusted R-square	0.104593
Root Mean Square Error	2.764646
Mean of response	6.142857
Observations (or sum weights)	98

As can be seen from Table 10, students in the SLIFGIL group performed statistically significantly better than students in the SWH approach science majors group and chemistry majors in the Honors-SWH group. Further analysis of student work on this problem revealed that students often took $\Delta H=q$ at constant pressure and most of them who had errors were more keen to just plug in the equation $q=mC_s.\Delta T$. Students who understood the law of conservation of energy applied that idea of $q_{solution}+q_{reaction}=0$, hence $q_{solution}= -q_{reaction}$.

Analysis of variance showed the main effect of instructional approach on student performance on the thermochemistry problem $F(2, 95)=6.66$, $p=.002$. The post-hoc analysis using Tukey's HSD (Table 14) indicated that the SLIFGIL students denoted as group T in Table 12 (M=7.41, 95% CI [6.47, 8.35] showed statistically significantly better performance than the Honors-SWH chemistry majors indicated as H (M=4.93, 95% CI[3.96, 5.90]. Comparison between the control group SWH group and the Honors-SWH group of chemistry major students also instructed by instructor facilitated SWH show no statistically significant difference (M=6.00, 95% CI [5.02, 6.97], p=1.009.

Table 12: Means for one-way ANOVA.

Level	Number	Mean	Std. Error	Lower 95%	Upper 95%
C	32	6.00	0.48872	5.0298	6.9702
H	32	4.93750	0.48872	3.9673	5.9077
T	34	7.41176	0.47413	6.4705	8.3530

Note: Std. error uses a pooled estimate of error variance.

Table 13: Means and standard deviations for one-way ANOVA-thermochemistry problem.

Level	Number	Mean	Std. Dev.	Std. Error Mean	Lower 95%	Upper 95%
C	32	6.000	2.91824	0.51588	4.9479	7.0521
H	32	4.93750	3.17183	0.56071	3.7939	6.0811
T	34	7.41176	2.13368	0.36592	6.6673	8.1562

This is also evident from Table 14 and Table 15 wherein the positive values show statistically significant differences and the levels that are not connected by the same letter as being statistically significantly different, for example the students in the SLIFGIL group differ significantly from students in the honors group receiving SWH based instruction.

Table 14: Thermochemistry problem post-hoc comparisons using Tukey-Kramer HSD.

Level-Level	Difference	Std. Error Diff.	Lower C.L.	Upper C.L.	p-value
T-H	2.474265	0.6809214	0.852977	4.095552	0.0013*
T-C	1.411765	0.6809214	-0.209523	3.033052	0.1009
C-H	1.062500	0.6911614	-0.583169	2.708169	0.2782

* α=0.05; ** q=2.38

Table 15: Abs (Dif)-HSD.

	T	C	H
T	-1.5965	0.2095	0.8530
C	-0.02095	-1.6457	-0.5832
H	0.8530	-0.5832	-1.6457

Note: Positive values show pairs of means that are significantly different.

Table 16: Level-wise comparison.

Level		Mean
T	A	7.4117647
C	A B	6.00
H	B	4.934750

Note: The levels not connected by same letter are significantly different.

The second research question is about the comparison of student laboratory reports for the treatment and the control group. Laboratory reports of students were compared for the stoichiometry based activity using the laboratory report scoring matrix developed by Choi, Hand, and Yager (2008), the difference was analyzed for student Beginning Question(s), Claim(s), Evidence-Analysis, and Reading and Reflection quality between the SWH & SLIFGIL-based laboratory. Ten laboratory reports were analyzed from each of the experimental and the control groups for the stoichiometry-based activity "Identity of a Chemical Reactant." A brief description of the activity from the laboratory manual follows.

Overview of Copper oxide activity:

A bottle containing a red powder is labeled "Oxide of Copper." Heating measured portions of the red oxide of copper in open air results in a chemical reaction. Is the original red powder pure powdered copper metal that has been mislabeled, or some other compound? To do this analysis, you and your classmates should divide into groups to design experiments, to run several experiments, and to collect data. Some of you will decide to perform specific experimental runs; others will choose to replicate data. Each person should conduct the experiment at least once. As a group, you should decide what information to tabulate on the chalkboard. Working with your classmates, write a balanced chemical equation that represents what happens when the red powder is heated. Is this a chemical reaction or a physical process? If it is a chemical reaction, classify the type of reaction**.** Note: The apparatus, materials, and reagents available to use are provided in the lab manual. (See Appendix F for a copy of the activity from the laboratory manual).

The SWH approach laboratory format in general has the following components:

a) Beginning questions.

b) Safety.

c) Procedure outline.

d) Data, observations, calculations and graphs.

e) Claim(s).

f) Evidence and Analysis.

g) Reading and Reflection.

Only student beginning question(s), claim(s), evidence and analysis, and reading and reflection were analyzed.

Based on the matrix, the beginning questions representing highest quality are given a score of 5. Report getting a score of 5 for the beginning questions meets following criteria:

1. Multiple questions (include more than one open ended questions).
2. Questions are testable and scientific in nature.
3. Capture the essence of the activity.

4. Questions are very significant for the activity and adequate to meet the learning objectives.

The beginning questions receiving a score of 1 are of low quality and closed-ended, poorly framed, not testable and have very little or no connection with the activity. In case of student claims, evidence and analysis, and reading and reflection a score as high as 5 indicates a high quality and a score of 1 indicates poor quality of these components of the SWH-based report. (See detailed matrix in Appendix D).

Table 17 represents the distribution scores on student-laboratory report quality. Students in the SLIFGIL group scored higher on the beginning question, claim(s), and evidence and analysis component of the laboratory report. However none of the students reports sampled showed a high score of 5. The highest score for beginning question(s) was 4 for SLIFGIL students whereas 40% of students in the SWH group scored 4 and 60 % had a score of 1 as compared to 70% of SLIFGIL students scoring 3 on beginning questions. A similar trend was observed for the claim(s) and evidence and analysis.

The students in the SLIFGIL-based laboratory scored higher on the reading and reflection component with a score of 5 for 20% of the reports and a score of 3 for 60% reports. Overall the score distributions indicate a better quality of laboratory reports from the SLIFGIL students. The students in the SLIFGIL-based laboratory scored higher on the reading and reflection component with a score of 5 for 20% of the reports and a score of 3 for 60% reports. Overall the score distributions indicate a better quality of laboratory reports from the SLIFGIL students.

Table 17: Score-distributions of student's lab-report quality on a stoichiometry-based laboratory activity: Comparing lab reports of SWH instructor-facilitated students with SLIFGIL students.

Score	5	4	3	2	1	0
SWH-students Beginning Questions						
Score Frequency	-	-	4	-	6	-
% Distribution	0	0	40%	0	60%	0
SLIFGIL Students-Beginning Questions						
Score Frequency	-	2	7	-	1	-
% Distribution	0	20%	70%	0	10%	0
SWH Students Claims						
Score Frequency	-	-	3	6	1	-
% Distribution	0	0	30%	60%	10%	0
SLIFGIL Students Claims						
Score Frequency	-	3	5	1	1	-
% Distribution	0	30%	50%	10%	10%	0
SWH Students Evidence & Analysis						
Score Frequency	-	-	3	7	-	-
% Distribution	0	0	30%	70%	0	0
SLIFGIL Students- Evidence & Analysis						
Score Frequency	-	4	3	3	-	-
% Distribution	0	40%	30%	30%	0	0
SWH students Reading & Reflection						
Score Frequency	-	1	4	3	2	-
% Distribution	0	10%	40%	30%	20%	0
SLIFGIL Students-Reading & Reflection						
Score Frequency	2	-	6	2	-	-
% Distribution	20%	0	60%	20%	0	0

To further ascertain the quality of student laboratory reports, non-parametric statistical tests were performed (Erceg-Hurn, and Mirosevich, 2008). The non-parametric tests are also known as distribution free tests as these do not depend on parameter estimates like parametric statistical methods. The non-parametric statistics have fewer assumptions; they can be used with rank-ordered data; they can be used with small samples; the data is not required to be normally distributed and outliers can be present (Coder and Foreman, 2009) . The reason non-parametric statistics were used for quantitative analysis of the quality of student laboratory reports is due to the small sample size with N=10 for each group (SWH students and SLIFGIL students). For non-parametric statistics, the accuracy of the probability statement does not rely on the shape of the distribution and it is unaffected by the sample size. The small sample size does not lead to misleading results (Leech and Onwuegbuzie, 2002; Siegel, 1956; McSeeny and Katz; 1978). (Hollander and Wolfe, 1973) lists some advantages of using non-parametric statistics:

a) They require fewer assumptions about the population as a data source.
b) Normality is not a necessary assumption.
c) They are easy in application as compared to parametric tests.
d) They serve well in situations where parametric assumptions are not met.
e) They are slightly less robust under situations when the distributions are normal (but are assumed otherwise) but are very efficient under non-normal conditions of distribution.

In parametric methods, the t-test is used for stated significance based on the assumption of normality. However when the sample size is small, an alternative to t-test may be the Mann-Whitney U test which is a better test under certain circumstances even though it reduces the observations to ranks and may be regarded as the test of the randomization type applied to the ranks of the observations (Moses, 1952). Two unrelated samples can be compared using non-parametric the Mann-Whitney U test also called the Wilcoxon rank sum test (Corder and Foreman, 2009). The Wilcoxon test performs the test based on Wilcoxon rank scores. The Wilcoxon rank scores are the simple ranks of the data. The Wilcoxon test is the most powerful rank test for errors with logistic distributions. A Kruskal-Wallis test is performed when there are two or more levels for the factor.

Table 18 displays the summary statistics for the laboratory report quality for the SLIFGIL and SWH instructed students for the quality of beginning questions, claim(s), evidence, analysis and reading and reflection components of the laboratory report. A Wilcoxon rank test/ Kruskal-Walis test was performed on the scores that were obtained based on Choi and Hand (2008) scoring matrix. These scores were analyzed for the differences between the means in the JMP statistical package using non-parametric methods.

Table 18: One-way non-parametric analysis of the key components of student laboratory reports for a stoichiometry based activity for the SWH group and the SLIFGIL group using Wilcoxon/ Kruskal Wallis tests (Rank-Sums).

	SWH Group (N=10)	SLIFGIL group (N=10)
Student-Beginning Question(s)		
Mean-Rank	7.60	13.4
Sum of Ranks	76	134.0
	S=76; Z=-2.12224; Prob>|Z|=0.0155*	
Student-Claims		
Mean-Rank	7.80	13.2
Sum of Ranks	78	132
	S=78; Z=-2.12224; Prob>|Z|=0.0038*	
Student-Evidence & Analysis		
Mean-Rank	13.1	7.90
Sum of Ranks	131	79
	S=79; Z=-2.10057; Prob>|Z|=0.0357*	
Student Reading and Reflection		
Mean Rank	12.4	8.60
Sum of Ranks	124	86
	S=86; Z=-1.50854; Prob>|Z|=0.1314	

A Wilcoxon Signed-ranks (Mann Whitney U test)/ Kruskal-Wallis test indicated that the quality of the laboratory report component for students in the SLIFGIL group was higher than the students who were in the SWH group. In the case of each of the components, the median (Mdn), Z= is a test statistic for the normal approximation test and is reported only when the X factor has two levels; S= gives the sum of the rank scores and is reported only when the X factor has two levels and measures the effect size (r) which is calculated by dividing Z by the square root of N ($r = Z / \sqrt{N}$). The summary for each of the components is as follows:

a) Beginning Questions (Mdn=3), S=76; Z=2.12, p=.0015; r= 0.67.

b) Claim(s) (Mdn=3), S=78; Z=2.12,p=.003; r=0.67.

c) Evidence & Analysis (Mdn=2.5), S=79; *Z*=2.10; p=.035; r=0.66.

d) Reading & Reflection (Mdn=3), S=86; *Z*=1.50; p=.013; r=0.47.

Based on nonparametric tests there appears to be no statistically significant difference in the quality of reading and reflection component of the laboratory reports for both groups in the study. One plausible explanation could be that students in both the groups are encouraged to complete all the components of the laboratory during the laboratory meeting in the presence of their peers and instructor. Students only write the reading and reflection component of the laboratory on their own after the laboratory session gets over. At this point students in both the groups are outside the zone of proximal development and working on their understanding of the laboratory activity and related concepts individually without any external aid. The zone of proximal development (ZPD) may be defined as a distance between what an individual can accomplish alone and all that they are capable of accomplishing when in contact with a more capable peer or an instructor. The role of the capable peer or an instructor in this situation is to prompt, model, explain, ask leading questions, discuss ideas, provide encouragement, and keep the student engaged with learning and focused on the context. These interactions between the individual and capable peer occur in tutoring situations; during cooperative/collaborative learning activities, and in sibling relationships. In the ZPD, the use of language and interactions among individuals lead to new mental structures and hence learning (Jones, Rua, and Carter 1998; Carter, and Jones, 1994; Forman, and Cazen, 1985).

The carry-over effect of SLIFGIL student role implementation was studied further in the second semester of general chemistry. Students who participated in SLIFGIL laboratories were monitored for their progress in the second semester general chemistry 178 Chemistry II course. Not all the students from general chemistry I enroll in general chemistry II the following semester. During the second semester, students received laboratory instruction using the instructor facilitated SWH approach and no SLIFGIL (SWH with student roles) was implemented. Assessment of student performance in the SWH approach laboratory activities and the carry over effect of SLIFGIL was done based on total points for hour exams, score on an ACS Final General Chemistry Exam and score on laboratory practical test. Students who continued in the second semester of general chemistry had the same lecturer, same text book, same HW problems, same lab procedure (SWH/guided-inquiry). The students tracked in this study were students from General Chemistry I who took General Chemistry II in next semester. The study thus had:

a) SWH students from General Chemistry I from the SWH group who continued in the SWH approach laboratories in the second semester.
b) SLIFGIL students who were now in SWH approach laboratories in the second semester.
c) TAs who taught using the SWH approach (SWH group roles were not implemented).

Table 19 displays a summary of student performance. The SLIFGIL students (n=29) had higher means on hour exams during the second semester of general chemistry, but the means are not significant as compared to the students in the SWH group. A similar trend is observed for the ACS general chemistry exam with SLIGIL students having a higher mean as compared to SWH students (112.73 vs 108.67; p|t|=0.49). As for laboratory practical exams, an independent samples t-test indicated that the scores were statistically significantly higher for students in SLIFGIL group (M=21.10, SD=2.24) than for SWH students (M=19.55; SD=3.02), t(55.21)=2.27, p=.02, d=0.58.

Students in the second semester of general chemistry were also compared for the performance on a problem related to acid-base buffers. The study of buffer solutions is studied during the second semester of general chemistry. The concept builds on student understanding of acid-base reactions, salt formation, and solution stoichiometry. Students were assessed for their performance on the following problems during the hour exam II:

Table 19: Carry-over effect of SLIFGIL implementation on student performance during the second semester of general chemistry.

	SWH (N=31)		SLIFGIL (N=29)		Statistical Analysis	
	Mean	SD	Mean	SD	t-ratio	Prob>|t|
Exam 1	69.09	14.76	75.4	14.6	1.66	0.1
Exam 2	71.22	12.9	72.0	16	0.23	0.8
Exam 3	71.38	2.71	74.72	2.80	0.85	0.39
ACS Final Exam (150 points)	108.67	26.08	112.73	19.51	0.68	0.49
Lab Exam (24 points)	19.55	3.02	21.10	2.24	2.27	0.02*

Problem 1- Buffers (multiple choice question-3 points**)**

Assume that standardized aqueous solutions of each of these are available. A classical buffer with a good capacity with desired pH=5.0 would be conveniently prepared by appropriate mixture of ________

a) HF and NaF
b) $CH_3COO^- Na^+$ and HF
c) $CH_3COO^- Na^+$ and CH_3COOH
d) NH_3 and NH_4Cl
e) CH_3COOH and $NH_4^+Cl^-$

Problem 2- Buffers (20 points**)**

Consider a 1.0-L buffer solution containing 0.15 M HF and 0.25 M NaF. [K_a=6.8x10^{-4}]

a) Write the principle equilibrium equation for this buffer system.
b) Calculate the pH of the above buffer solution at 25 °C. (Show an ICE table, check your assumptions (if any), and use correct number of sig. figs. for full credit).
c) What will happen if 0.050 mol of HCl is introduced into the above buffer? Write a chemically balanced equation to justify your answer.

d) Calculate the pH of the above buffer solution after addition of 0.050 mole HCl. (Show all steps for full credit.

The correct solution for problem 1 is answer choice c) ($CH_3COO^- Na^+$ and CH_3COOH). For solving problem 2 students have to correctly write the equation (for rubric, Appendix E).

$$HF_{(aq.)}+H_2O_{(l.)} \rightleftarrows F^-_{(aq.)}+H_3O^+_{(aq.)}$$

Based on the above equation, an ICE table is constructed for the molar concentrations of HF, F^- and H_3O^+ and the pH is calculated using the equations $K_a=[H_3O^+] [F^-]/ [HF]$ and $pH=-\log (H_3O^+)$ and pH =3.39. Addition of an acid further changes the pH of the buffer solution leading to formation of the acid (HF) and the chloride ion (Cl^-). The final concentration of the buffer solution after the addition of the base may be calculated by constructing an ICF table representing the molar concentration of each of the species HCl, F^-, HF & Cl^- present in the resultant solution. A new ICE table is used to indicate the HF, H_2O, F^- and H_3O^+ concentrations. The pH of the resultant solution is calculated using the concentration of H_3O^+ and should equal 3.17. Ninety-three percent of the students who experienced the SLIFGIL approach during first semester of general chemistry chose c as compared to 70% students in non-modified SWH based laboratories (Table 20).

Table 20: Distributions for student response to multiple-choice type buffer problem 1.

	Choice a	Choice b	Choice c	Choice d	Choice e
SLIFGIL (N=29)	1 (3.4%)	0	27 (93.10%)	0	1 (3.4%)
SWH (N=31)	1 (3.22 %)	4 (12.90%)	22 (70.96%)	1 (3.22%)	3 (9.67%)

Table 21: Analysis of student performance on buffer problem for students in second semester of general chemistry.

	SWH (N=31)		SLIFGIL (N=29)		Statistical Analysis	
	Mean	SD	Mean	SD	t-ratio	Prob>|t|
Buffers Problem 1	2.12	1.38	2.79	0.21	-2.271	0.0268*
Buffers Problem 2	12.61	0.57	17.60	0.59	-6.059	<0.0001*

Further analysis of student performance on buffer problem 1 was done using t-tests (Table 21), which indicated that scores of the students in the SLIFGIL group were higher (*M* = 2.79, *SD* =0.21) than the scores of students in the SWH group (*M*=2.12; SD=1.38), t(47.68)=2.27; p=0.02, d=0.67. Comparison of student performance on the second buffer problem using the t-test indicates that students in the SLIFGIL group scored statistically significantly higher (*M*=17.60; sd=0.59) than the students in SWH group (*M*=12.61; SD=0.57), t(53.71)=6.05; p=.0001, d=8.47.

Qualitative Video Data

The qualitative data was used to find evidences of differences between a) how the SWH and SLIFGIL based laboratory sessions differed and (b) interaction patterns of students during a laboratory activity when using the SLIFGIL approach and SWH approach. The quantitative findings show that students receiving SLFIGIL instruction perform better on hour exams and specific exam problems about various topics in general chemistry. The underlying question is- what is the difference between the SWH based and SLIFGIL based laboratories when the student roles are implemented. Does the implementation of student roles lead to changes in interaction patterns among students in SLIFGIL based and SWH based laboratories. The qualitative video data was thus used to further highlight the differences between the SWH laboratory instruction and the SLIFGIL approach.

Comparison of SWH and SLIFGIL based laboratories session

Pre-laboratory session in SWH and SLIFGIL based laboratory

The opening session of the SWH laboratory as well as the SLIFGIL laboratory begins with students moving across the laboratory collecting their equipment trays. As students walk in, the laboratory gets busy and noisy. There is a difference in which the teaching assistants open the session for the SWH based laboratory and the SLIFGIL based laboratory. While the SWH teaching assistants summarize information on the board, the SLIFGIL teaching assistants were seen surrounded by a group of students. The SWH teaching assistant addresses the laboratory group while standing in the center in front of the chalkboard; the SLIFGIL teaching assistant is more involved with students in the corner of the room.

SWH-CuO laboratory: opening session

TA 1 has written following things over the chalkboard before beginning the lab-session, perhaps they were written before student entered the laboratory.

Beginning Question

Safety

Procedure outline

Data, observations and calculations

Claims

Evidence & Analysis

Reading and Reflection

TA 2: for those of you who have not turned in your lab report, you have to turn in your lab report now for ‘observation of chemical reaction.’ You may put your lab reports here on the table…..so everybody has turned in their lab reports…I want to draw your attention to something which is coming up next week…you need to have the pre-lab for the conversion of chemical reactions and identity of a chemical compound…that is the next experiment on in your manual…your safety assignment is due next week…the first safety assignment…

S1: I thought its due this week.

TA: ...*moves closer to the student, not visible in video,* What does it tell in your syllabus?

S2: It says it’s assigned this week but it’s due the week after that.

S1: Oh……*tells that he did it assuming it this week.*

TA: It’s okay, you are ahead!

TA cleans the portion of chalkboard that has information regarding the activities due next week which she has also told to the students and moves on the discuss the pre-lab further.

SLIFGIL-CuO laboratory: opening session

There is nothing on chalkboard. TA starts distributing lab reports from the past week. Students stop by to talk to TA.

S1: Do we know which group is leading the lab today. Is that our group?

TA: We will soon know it.

S2: Oh! Come..on. is it our group..today..?

TA: (smiles) you got to wait…

During a safety and procedure pre-lab, the following interchange took place in SLIFGIL based laboratory:

Safety:

Kevin: So regarding safety folks……you have want to make sure that…what?

Bekka: Ok Kevin we know that we have to wear our goggles, apron and gloves…

Kevin: Yes, but like Sonya says, what are we working with.

Mike: Copper or copper oxide, some red powder that we don't know what it is.

Kevin: Okay so how it is …what you say..harmful?

Mike: Oh you mean don't swallow it.

Kevin: Yes and what else. Sonya is that it?

TA: Kevin what about equipment and where do you want the class to discard stuff?

Kevin: Oh yes folks you want to be careful of hot things and also use waste bottles to throw away the waste….

Procedure:

Kevin: Hey Kilo you are procedure expert so teach us what we are doing.

Kyle: I am not telling you. I have to help you figure out? So everybody what do we need to use to answer the beginning question.

Joe: Gas burner.

Kyle: What else? Anybody wants to quickly tell all what do we need?

Rob: We need an evaporating dish, crucible tongs, weight boats to mass the red stuff.

Kyle: Okay we mass the red stuff.

TA: (Interrupts) So why do you need a weigh boat?. What do you know about red stuff? What are its physical properties?

Seth: It is a powder, solid, it is red.

TA: Yes but are the particles small, big, fine? What will happen if you mass the powder on a weigh boat?

Ryan: You will need to tare the scale.

TA: Kyle, I am sorry to interrupt but I want to know from your class if it is a good idea to use a weigh boat to get the mass of the red powder or we can use something we have mentioned?

Kyle: I don't know what does everybody think here? What should we do?

Mike: We are trying to get the exact mass of the dish so I think Sonya is saying that we need to just use the dish for getting the mass of red stuff.

Kyle looks at Sonya.

TA: Go on Mike. Why?

Mike: because you said that it is fine powder….

TA: So what about the fine powder?

Mike is quiet. Courtney adds..

Courtney..it may still remain on weigh boat..so you mean we can get the powder to dish directly is that why we are getting constant mass.

TA: Over to you Kyle.

Kyle draws set-up on the board with gas burner, clay-pipe triangle and evaporating dish and then asks his peers, if they think this is what they will be doing.

TA: What mass you want them to use Kyle?
Kyle: Okay you want to tell me what is the mass you will be using?
Jake: It says that we have to use between 0.150-0.250 grams of red thing.
Kyle: Okay so mass 0.150 (grams) to 0.25 (grams) of the red stuff in your dish.
Steph: So we do that after the constant mass of the dish.
Kyle: What does everyone think?
Mike: I guess that's what sounds right. You constant the dish.
Kyle: Sonya one thing I want us all to understand is that why are we heating dish. Why can't we just clean it or use it right away?
TA: Kyle you tell me why should we heat it. You mentioned "constant the dish". Why should we constant the dish?
Steph: Because there could be some stuff sticking on the dish. Like some of them are black over there …contamination or something.
TA: So Kyle what would you say based on what Stephanie just mentioned?
Kyle: Okay, so folks do you have questions on why are we heating the dish to constant mass? I guess I understand that…
Jasmine: Again so why are we heating the dish?
Kyle: I guess you will have to see the dishes to say that, are you 100 percent sure your dish is clean to begin with.
Jasmine: …Okay so in a way we are cleaning our dish by heating.
Kyle: So you are heating dish getting mass and then what?
Kim: You are adding red stuff not to weigh boat but to dish and getting the mass.
Sonya: How would you know what mass everybody is using. Do you want everybody to use the same mass?
Kyle: No I guess, Sonya can we make them note somewhere what mass each person is using.
TA: Would you like replicates of some?
Kyle: Yes we need at least 3-4 people use similar mass.
TA:Why do we do that Kyle?
Kyle: Class, why should we have repeat for same mass? Does anyone know that?
Nick: Because one run may have error, we can average if we have 3-4 runs for same mass.
Kyle: So I guess we are done and Sonya set up the equipment.

Materials and resources SWH and SLIFGIL based laboratories

Students in the SWH laboratories are seen using the laboratory book, notebook, and their standard laboratory equipment trays. Students in the SLIFGIL laboratory use name tags with their names written with a marker pen and a letter in the corner of the name-tag. Students are wearing their goggles, apron and gloves in both SWH and SLIFGIL laboratories. In addition, it is seen that a 12/20 students in SLIFGIL-based laboratories are using a spare notebook besides their regular laboratory notebook. When asked about why they have a spare notebook, 9/12 students mentioned that they took extra notes related to the laboratory in there. 3/12 students mentioned that they like to organize their work and hence the additional notebook helps them track their work and keep presentations neat.

Post-laboratory discussion in SWH and SLIFGIL based laboratory

In case of the SWH based laboratory, clearly the instructor is in charge of the laboratory and students rely more on the instructor as compared to their peers for experimental work and calculations. This is also evident from the frequencies of student-student interactions as compared to student-TA interactions and student group-TA interactions (Table 22). In the SLIFGIL-based laboratory, there is a some shift in student interactions with one another during the post-laboratory discussion as the instructor assigns roles. Students are aware that they need to communicate with the student experts and vice-versa when making claims and providing evidence during the post-laboratory discussion session for example:

> Student: My claim would be that the empirical formula of our unknown red compound is Cu_2O.
> Student (expert): How do you know that? What evidence do you have?

In the SWH-based laboratory, the instructor gathers students and asks them about trends in the data, anomalies, and asks them to make a claim and share their evidence for example:

> TA: All right everybody, I want you to get in your groups and share your claims and evidences.
> TA: What were some sources of errors?

Then the instructor moves to a discussion of the big ideas, and introduces scientific terms pertinent to the laboratory activity based on student observations for example:

> TA: What did you learn from the lab today? What is the big idea?

In the SLIFGIL-based laboratory, the instructor facilitates the post-laboratory class discussion along with the student expert as shown below:

> TA: experts I want you to gather together and go over the beginning questions, claims and evidence first please.
> Student: So what is our class beginning question?
> Student: What can we claim and what evidences do we have for our claims?
> TA: based on the discussion, our big idea is (waits for students to respond)..?
> Student: law of conservation of mass.
> TA: Ok..Any other ideas?

Each expert takes over their roles again and then goes over the beginning questions, safety issues, data trends, anomalies, claims, and evidences. The instructor elaborates on the expert discussion by asking questions or rephrasing the expert ideas to engage students in reflection on the activity, errors, and connections between the concepts.

Interaction patterns in SWH and SLIFGIL based laboratory

Interactions play a major role in laboratory learning. In traditional laboratory settings, the instructor plays a lead role and is the only person talking and giving directions for most of the three hours that students spend in the laboratory. Students have a procedure that outlines step by step directions and instructions on what to expect for each step that occurs during the experiment. The interactions that occur in such a directive environment may be exemplified as follows:

> Student: Am I doing this right?
> Student: Can you please look over my experiment and tell me if I have set up everything correctly?
> Student: Can you check my calculations and see if they are as shown in the procedure?
> Student: I am done with my experiment. Can I leave now?

The instructor's response in such a situation is either an affirmative yes or a no and the role dims down to checking the set-up, looking at calculations and confirming whether the steps undertaken by the students are consistent with what is being directed by the laboratory manual. If one for assumes that everything that is in a given laboratory is safe for students, the laboratory is equipped with correct materials and equipment needed, and that the laboratory manual is written perfectly, then, actually, students don't even need the instructor there as his/her role is minimal in a scenario where the goal is technical set-up (which students can also see via a video) and just affirming whether things were done correctly.

As compared, for students in inquiry-based laboratories (which may be open-ended or guided-inquiry like the SWH approach), a lot of decision-making is required. It is a two-way process in which the instructor knows the learning outcomes of an activity and gently guides students in the direction of these outcomes; students are actively engaged in their learning process. The purpose of such an instruction is not verification of explicit outcomes but it is learner-centered and demands preparation and input on the part of the students. Students cannot leave the laboratory after completing with their part of the activity as it is collaborative, interdependent group work and requires student contribution to class data and discussions. Traditional settings are thus minimally constructive as students barely talk to each other, than in inquiry mode when working as peers, the purpose of the joint work is data collection and making/sharing observations besides joint experimental set-up and sharing of equipment.

In SLIFGIL-based laboratories, where students lead the laboratory in the expert role, the student leaders have to think through various aspects of their laboratory activity ahead of time. But since they are not yet aware how everyone is involved in the entire class as one large group, and how the experts as a sub-group would contribute to shaping questions, a lot of decision-making happens in the laboratory with peers as experts' peers in a group as collaborators and the instructor. This is a key difference between a SWH laboratory and a

SLIFGIL group. As evidenced by the video tapes, in a SWH-based laboratory, the interaction is mainly happening between students and instructor whereas in SLIFGIL-based laboratories, student-student interactions happen most.

Teaching assistant and student interactions are next. While in SWH laboratories some students contribute very little to the overall class discussion, in SLIFGIL-based laboratories there are few students being left out as everyone has to contribute to the class discussions due to student-expert with student interactions in addition to teaching assistant with student interactions and teaching assistant with student group interactions. Table 22 displays the frequencies of student-student interactions and TA-student interactions in SWH- and SLFIGIL-based laboratories followed by some excerpts from the video-recordings of both formats exemplifying these interactions.

Table 22: Interaction frequencies in SWH and SLIGIL based laboratories.

	SWH laboratories	SLIFGIL laboratories
Total interaction frequencies	557	453
Student-Student interactions	59 (10.59%)	111 (24.50%)
TA-Student interactions	282 (50.63%)	103 (22.73%)
TA-Student group interactions	216 (38.78%)	239 (52.76%)

For finding the frequencies of interactions, all the instances from transcripts of the three hour video for SWH and SLIFGIL laboratories were counted and classified as student-student interactions where two students are interacting with each other and their conversations were captured distinctly on the video. Similarly the interactions of the TA with individual students or with a group of students were counted and classified as TA-student interactions and TA student group interactions. Later the percentage of interactions was calculated for each kind of interaction based on the total number of interactions transcribed from the video clips per laboratory. As is evident from the Table 21, the interactions in the

SLIFGIL-based laboratories as well as SWH-based laboratories are in good numbers. The difference between the two laboratory approaches lies in the patterns of these interactions. Though SWH-based laboratories have a higher numbers of interactions for the same length of time compared to SLIFGIL-based laboratories, it was relatively difficult to code all the interactions due to lack of audio or video clarity on some spots. Examples of the three types of interactions for SWH based and a SLIFGIL laboratory are as follows.

SWH based laboratory

a) Student-Student interactions

Rick: my stuff is changing to dark color..um what does your look like. I guess I might be doing something wrong.
JK: I just started…don't know you might want to check with the TA.

b) Student-TA interactions

TA: What are you doing here??
Nolan: heating my stuff..the point (flame) is not quite underneath the copper dish..
TA: So are you gonna do anything differently
Nolan: I don't know..like I see its getting hot here.
TA: What are you looking for..why are you heating this red powder?
Nolan: Looking for some kind of change you mean..
TA: like what..
Nolan: color change I guess..

c) Student group-TA interactions

TA: what are you all doing here?
Sam: we did um …I think this will be our third time heating.
Joe: the mass went up when we did it two times so…we are just waiting to see what will happen to this one.
TA: So what do you all say about it? Why do you think mass is going up?
Karen: its adding stuff..
TA: adding what??
Max: Oxygen its gaining oxygen from air?
Sam: I thought it will break apart..when I was heating but seems like it is what Max is saying..gaining that thing..oxygen!
TA: Ok we will discuss that as a class. Did you start entering your data yet..
Max: we will after finishing up our heating..we are gonna work out calculations together.
TA: Ok!

SLIFGIL based laboratory

a) Student-Student interactions

Eric: all right guys so what is the big idea? Do we even have that on the chalkboard?

Courtney: Yes we do, take a look at the mole ratio one. It is just not worded correctly. That question should be about empirical formula. After all that;s what you get when you know the mole ratio.

Eric: why do you need to know mole ratio?
Courtney: Because you really don't know what your initial stuff is. You know that it can be copper or some compound of copper but it does not tell which of the either.

b) Student-TA interactions

TA: So what are you doing here?
Mike: I am heating my dish?
TA: Why do you need to heat the dish? What did you understand from Kyle on that part?
Mike: that we need to constant the dish.
TA: Ok, so what will you be doing after getting your dish constant.
Mike: I guess I will add the red thing to this dish. Hey Sonya (TA) can I ask you a question regarding the data..
TA: Is it something that would you seek Step's advice on first, and if you still don't have a solution sure we can look at it together.
Mike: Ok, where is Steph. Oh she is there.

c) Student group-TA interactions

TA: What do you think it is we talked about that. Read your experiment and I will come back again and would like to know what you have found. Did your red powder gain mass or lose mass after heating.
Jared (Steph, lab parter): It added mass.
TA: What was your initial thought?
Steph: I thought it will lose…
TA: Lose what.
Jared: Mass ofcourse!
TA: So what is happening here…can you provide a possible explanation of what is happening on heating red powder. Is this just your groups observation. Katie interrupts.
Katie: No we have other groups who have also similar things…
TA: like..
Steph: add mass.
TA: so what did you add…
Jared: what do you mean??
TA: what could have led to gain of mass…
Katie: May be something from air got in which ….
TA: What from air..
Steph.: oxy..oxygen.
Jared: but if our compound is Copper oxide how can it add oxygen..
TA: are you sure it is Copper oxide…
Katie…No we are trying to figure out that..it could be copper becoming copper oxide.

TA: how can you confirm it is copper oxide what is your evidence..
Steph: we gained mass so it could be copper going to copper oxide..
TA: Which oxide of copper..
Jared: Uh…
TA: What is your product going to be..
Katie: black…
TA: Yup..
Step: wait didn't we say that it would be copper II oxide..
TA: what is the formula can you write that in your journals..
Katie: yes…like this writes Cu_2O..
TA: so what is the charge on oxygen?
Jared: negative 2.
TA: so what should be the charge for copper which Katie is showing..(points to students notebook).
Steph: wait the copper is +1 here …so this cannpt be copper II oxide.
TA: so what would be copper II oxide..
Jared: you mean just CuO.

In both laboratory approaches, the TA-student interaction/ TA student group-interactions reveal that by correctly questioning students about their observations, they get an idea that they need to apply the concept of a limiting reagent to understand the experiment and pay attention to observable changes during the activity (find the original red compound is completely converted to coarse black solid). The student-student interactions and TA-student group interactions were found to be higher in SLIFGIL-based laboratories whereas the TA-individual student interactions were found to be higher in SWH-based laboratories. One plausible explanation for this difference could be due to the implementation of group roles in SLIFGIL-based laboratories. Students in courses using the SLIFGIL approach lead the laboratory as experts and are required to communicate with their peers, while in SWH-based sections the pre-laboratory and post-laboratory discussion is solely facilitated by the instructor. This explains why the TA-student interactions are higher in SWH-based laboratories. Similarly the TA-student group interactions are higher in SLIFGIL-based laboratories because the student experts communicate with the instructor as a group and also the instructor further interacts with each of the student groups as they work on the SWH approach, since the students work in pairs (another form of group) students rely more on their TAs as compared to relying on their peers from other groups for activity-based queries.

As found from the analysis of video transcripts, in SLIFGIL-based laboratories, students are asking questions to one another and the TA is asking questions to students individually or in groups. In SWH-based laboratories, the questions are mainly asked by the TA and are directed to individual students or student groups. The pre-laboratory phase is the point where students contribute their questions to the class and discuss class beginning questions but after that the student questioning decreases in the SWH-based laboratory. In the SLIFGIL-based laboratory, students lead the laboratory as a group of experts and are asking questions of the class as a group or involving the TA in questioning and even seeking help to frame good questions. Students are encouraged to share their ideas with each other by asking questions from each other instead of giving a direct answer to their peers. The questions being asked in the SWH-based laboratories are more directed toward seeking help or affirmation from the instructor about the procedure or confirming the calculations. When the instructor is asking questions they are phrased to derive input from the students and are directed to the individual student or student groups for example - “What are we doing here?” or “What is your prediction?” “How do you know it is copper?” In the SLIFGIL-based laboratory, the questioning involves frequent use of how, what why, and when kind of questions, but these are used by TA as well as students (example of script above).

In both the SWH- and SLIFGIL-based laboratory students talk about the experimental set-up to their peers or the TA. Students are mainly concerned about (a) their set-up and the flame configuration for the copper oxide activity and (b) in finding out when their reaction get over or (c) signs that they are done with heating. For example:

> Student1: For how long do I need to cook this stuff?
> Student 2: When does this (reaction) get over?

Findings from Interview Data

The interview questions were focused on the following aspects of the laboratory each of which is discussed in further detail:

- Student background in chemistry laboratory;
- Student view of implementation of group roles;
- Student view of the extent of engagement with the activity;
- Student view of the laboratory report format;
- Student suggestions for improvements that can be made in the laboratory instruction.

Student background in chemistry laboratory

Students interviewed were either freshmen or sophomores in chemistry. All the students interviewed had general chemistry as their first laboratory experience at Iowa State University. Students had experienced laboratory during the high school chemistry, which was, in general a 45-minute to 1-hour laboratory session. Students interviewed mentioned that the laboratories were connected with the class and they did an activity once a week or once a month depending on the instructor. (Pseudonyms are used for student names; I = Interviewer).

> Brad: Um my junior year (in high school), I had a chemistry lab but it was really like sort of timed like we had an hour to do everything.
> I: One hour to do everything?

Brad: Maybe forty-five minutes so everything was rushed and a lot of times you wouldn't even get your stuff done so..

I: So and this was your first chemistry lab 177L?

Cam: Yes!

I: And have you ever had chemistry in your school time or something?

Cam: In high school I took just general chemistry.

I: General chemistry okay so, uh, how do you compare your high school chemistry class or lab with your first year here?

Cam: Um, in my high school chemistry lab, we just had like worksheets that we would fill out when we did a lab.

Student view of implementation of group roles

During the interviews, students stated that the implementation of group roles kept them involved in the laboratory and improve their communication skills. Group role implementation had its own challenges, requiring students to be prepared ahead of time. Students benefited from this laboratory instruction format. Students also mentioned that they learned chemistry better when involved in the laboratory in this way as compared to their high school chemistry laboratory experience and were able to connect with the concepts taught in the lecture by applying what they learned in the lecture to laboratory or what they learned in the laboratory to connect with what was covered in the lecture. In addition, when asked about the role of the instructor, students mentioned that even though the students did most of the work in the laboratory as a team, their instructor was very much involved with them and would guide them through when they got stuck on any aspect of laboratory and were clueless of the next step.

Brad: Um, yes, I did like it, it everything was good. I didn't, I obviously didn't like chemistry, I came in and like uh I dreaded to come in the three-hour lab or whatever, but then after I got to understand everything and know what I was doing I like it. Now that its all done, I am glad that I got all the knowledge, and I know a lot more and its taught me so. I am happy with it. It was good teaching and good ways of doing it. I like, I like how she kind of told us what we had to do but then we had the kids coming and helping us do it so there is kind of two different ways of learning out there and they were kind of good for me anyway.

Josh: Um, I don't know I just with like the peer-led lab, I guess I don't really know about the instructor ones like I guess in kind of high school I did but um it seems like it kind of like makes you like feel more like a group kind of and like you know there is a lot of like team-work and working together and stuff and I think that's just it's a good way for me to learn anyways is just working with other people and you know all trying to accomplish the same thing. Um, yeah, during the lab there was like five different leaders and there the beginning question leader, the safety leader, procedure, uh data table and claims and evidence and um yeah, I like that a lot actually. It was a good format, um, like I enjoyed being the leader and you know getting to kind of feeling special I guess. And then, I was like, it was really good you know just to have someone there like taking charge kind of the whole group and be able to like ask them questions about it and stuff.

Evan: I have been in charge of beginning questions which is, like, you know, getting, uh, getting the whole class to be working on the same experiment and make sure that they are going after the same goal. I have been in charge of safety, um, and making sure everybody disposes all the chemicals in same place, making sure that if there is any broken glass we take care of it accordingly and making sure everybody is well-equipped for the lab. Um, I, oh, I was also in charge of the procedure making sure everybody was following the right procedure during the lab, um, and oh, and there was data table, um, which was making sure we got all the data neatly organized. I was never in charge of the claims, though.

Cam: Uh, you could be the beginning question person/leader and you would have every group write what question they had on the board and then we decided as a class what was the best question to apply to our lab. Or, you could be the safety person in which you would go over the safety concerns for that lab. And the procedure person would kind of just go over what we are going to be doing today pretty much. And then, there was, like, uh, claims persons in the end that would decide that so, from our data, what can we conclude about this lab. Like what's our findings? And, there is also a data person who would figure out what, um, what numbers we were looking (at) and then have entered it on the board and computer. We had to ask questions off each other.

Josh: Yeah, um, she did even though like the group leaders were, you know, like the leaders of the, um, like the lab like, you know, we had, like, questions as leaders or as regular groups. Our TA would always help us out and stuff. And she always knew what she was doing better than any of us so, like, she was always there for help to guide us through and ask us questions.

Evan: Um she was just kind of like a facilitator, like, you know, it really kind of like, you know, when we do everything on our own a little bit and then, um, she would like kind of give us feedback as to know if she thought we were headed in the right direction or if she thought maybe we were headed in the wrong direction. She would kind of steer us to what we probably should be doing. So she was just, she just kind of like provided guidance to help us stay on track.

Student view of involvement with the laboratory activity

Students felt that they were very much involved in the laboratory which led to a better and richer learning experience. Students expressed that they liked the way in which their laboratory was structured and their peers were the facilitators *along with* the instructor which helped them to focus, learn from the laboratory activity, and make connections between lecture and laboratory instruction.

Brad: The high school, not the high school but the college one helps me learn a lot better. Because they are actually pushing you and you are working hard at it. Yeah, you understand it, [high school laboratory] you just don't kind of see it and it just goes right, whoosh, out in one ear and out through the next and you are, like, oh, ok. So, actually, you understand what you are doing when you are done. Yes, I connected some [concepts with lecture], there was a lot I still didn't understand but I knew a lot more when I was done than when I started, so I felt like that helped me a lot. Some of the things that were in my lab class, yeah, with the just chem. 177. Yeah, it connected together well. Like when we do experiments and whatever you would, uh, do your titrations whatever we were going to do, and you do the formulas, and then when you have your questions in chemistry they have the same idea and then they talk about the things you did in lab. And, they, it kind of connect with it, and then you understand, oh, yes, that's what I did in lab and its how I got to do it with this equation. I can get it right, so.. Um, I just like said pretty much I liked just how the class, like, we got involved in it, and pretty much did it ourselves. Which is the best teach yourself pretty much learned from yourself and learned from what you do. And there wasn't really anything that I didn't like. It gets kind of long, three hours, but you almost need it, standing up there for three hours the first day. I get in there I was, like, wow there is no chairs. I got to stand here for three hours and this is morning and I got to starve in for noon to come so that you could go to lunch, but it turns out that everything is good. Yeah that's pretty much it I guess.

Cam: Um, here it was kind of more independent learning like we got to apply the things we learned in class in the lab and sort of it has helped me learn it better because you know I could see a way to apply it and yeah.

Josh: Um, like my involvement like, I got to be a leader probably like, three or four times. And, uh, so I was involved in that way. And then, just, you know, when I wasn't leader, like it was very, like uh, I don't like the whole group participating. Like if you know if we all tried to decide the beginning questions and then you know, we all went through the procedure and, like, what we were doing. And all the safety stuff like, you are very involved the whole time there was not a lot of, like, just standing quietly, so which is good I think.

Student view of laboratory format

Students were asked to compare the format they had used in the high school and how it was different from what they did in Chemistry 177 laboratory. All the five students mentioned that they were required to write a lot in the SLIFGIL-based laboratory and actually explain their observations and data. Students indicated that their prior chemistry laboratory report format was more fill-in-the-blank format. In their report writing, students felt they had to think and explain (a) what they did and why they did it, (b) errors, (c) applications and (d) how their laboratory connects to what they did in lecture. As compared to their high school laboratory report writing experience, all students who were interviewed felt that the format in their college chemistry course was more in-depth, laid-out, and very specific which helped them learn better from the laboratory.

> Brad: We didn't really have a lab [high school], I was like, I guess, it was that you just saw, he'd like give you a worksheet and you just write down what you think. It was really what you put, you would have not, like, a thing you said, like, calculations or anything. It was totally different. Here it was specific. It pretty much said what you need to do and not as much, I know, everyone that you could pretty much write anything down and turn that in. Uh, it would be like, kind of fill-in-the-blank, like you would have figured it out. And now that you fill that blank in there and like write what you just thought about it but it wasn't, like, it was totally different than from here. Because, here you had to go in detail and then you had to actually do it. But high school, you just kind of whatever you just wrote it, we did not take it serious at all. Here it is more a lot more serious. Well obviously college [format is better], because it's not a joke. You actually do it. It's like your own job, seems like that's, like, the way I take it. So you got to do it, and you got to do good at it otherwise you fail so.

> Cam: I think here [format is better]. Because it's more than just, uh, more than just filling out a worksheet about it. Like you actually have to think, okay, how does this happen, how does this reaction, how is this reaction happening? Why does this happen? What causes this and like why is this important? ..Um kind of thing.

> Evan: Well, I really liked the lab format here because, um, we got, we got more experience in working with groups and we had to actually figure out what we were doing before we did it so instead of simply just answering a question, we were able to figure out why we had to answer that question and how to answer that question. I definitely liked the way 177 was set up with the lab reports because, um, it made you do enough before the lab that you fully understood it, but it didn't make you go do a ton of work before you did the lab because, after the lab, then you had to do the discussion of reading or reflection so that you learned more about what you did, so that you can understand it better. But, I am glad we didn't have to do it before so it may have been confusing or given us answers to our lab that we didn't know yet um, but, yeah, I think it was set up very well.

> Josh: Um, I just think it (the format) was conducive for learning. I think just, um, it helped me just you know understand what was going on and everything and yeah! It just kind of helped me like, specially like the evidence and analysis section, um, that really helped me just kind of think about like, it, you know, like, you know, like what we really did that will help support the claim that we made. And you, like, the claim answers the beginning questions, so you know all this kind of tied it all together. And, uh, so the evidence was really what I thought was good, because it helped me just think about it and think about what was actually happening.

> C: Um, oh, I liked, I liked that we were more involved with what we are going to be doing that day in lab. And I liked that it was kind of more independent stuff that we did, um, my dislikes Maybe it took a lot of time at the beginning of class to go over everything but, I mean, after we started doing the lab, the time went by faster. So it was, uh, we were kind of if other labs said oh we got done in a hour and we'd be still taking the three hours. But, I mean, I think we probably learned a little bit more than they did maybe by going over stuff. That's good.

Student opinion on improvements that can be made in the laboratory instruction

Students were overall satisfied with the laboratory experiments that they had in the syllabus. One student out of five who were interviewed wanted to type in the laboratory reports but the other students suggested including activities that were more visual, included a description of the equipment to be used and lay out more expectations in the syllabus so that they understood beforehand the level of involvement they would have in the laboratory with the activities.

> Dan: Yeah, like more on certain techniques, like when you are up there doing in front of students the set-up like like a buret or a flask, like, you know, that and can do it well in your roles. So, yeah, some more time with techniques would be better we did that, but it could have been done better if I had just gone through it myself. But I believe the way it was structured, we did it with our peers, and it helped.

> Evan: One thing I was thinking about is you could include an equipment section in the lab report, probably in the pre-lab, where you have to do the beginning questions, safety and then I was thinking an equipment section where to know what equipment you are going to be using in the lab and what it is usually used for because you can use certain things to perform certain labs.

Conclusion(s)

The findings from the quantitative and qualitative data indicate that students are more engaged in SLIFGIL-based laboratories when assigned group roles and they perform better on hour exams, the ACS final exam and laboratory practical exam assessments. Further, SLIFGIL students show improvement in their quality of laboratory reports as compared to the reports from the students in the SWH group; students in the SLIFGIL group showed statistically significant differences in their laboratory report quality. It was also found that the students' understanding of the SWH format improved. In 4-5 weeks, students in SWH-based laboratories in general displayed improvement in their understanding of the laboratory report format. Students in the SLIFGIL-based laboratory improved by their third week of writing reports, having experienced the format via their role implementation and doing it as a group instead of by an instructor-moderated approach. Findings from the qualitative data indicate differences in between the SLIFGIL and SWH based laboratory especially the pre-laboratory and post-laboratory session with respect to students leading the laboratory in facilitation with the instructor as compared to SWH based laboratory in which the instructor is the sole facilitator. In addition, student-student interaction is higher in SLIFGIL based laboratory as compared to student-student interactions in SWH based laboratories.

Challenges with implementation of student roles

At the beginning, implementation of group roles was a challenge as it faced TA resistance. Out of six teaching assistants signed up for the study, only two teaching assistants continued with the study for the entire semester. Not all students accepted signing up for the study to undertake group roles. Although they actually participated in the roles, their data is not included in the study. At times the pre-laboratory session lasted much longer, frustrating the teaching assistants but they mentioned it was all worth it. As the semester progressed students became more organized and were more communicative in the laboratory.

Further studies:

Further studies are required on a larger scale to study the impact of implementing SLIFGIL. In addition student attitudes and instructor attitudes need to be studied pre- and post-study to see whether the implementation of student roles brings about a significant change in student and instructor attitudes on laboratory instruction.

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CHAPTER 4

GUIDED-INQUIRY BASED INSRUCTION AND ITS IMPACT ON THE CRITICAL THINKING ABILITITIES OF STUDENTS

Abstract

Students in traditional laboratory instruction use the verification approach for experimentation. Students in a senior level chemistry courses are more experienced with chemistry as compared to college freshmen and sophomores via the laboratory reports. In this study an examination is made of the critical thinking skills of freshmen students in a guided-inquiry based general chemistry laboratory in which the Science Writing Heuristic approach is implemented, engineering majors in freshman general chemistry for engineers using a traditional verification approach, and senior level chemistry students using a traditional verification approach. By comparing the student laboratory reports at the two levels of college chemistry it was found that that students engaged in guided-inquiry based laboratories have a higher level of critical thinking as evident from the analysis of student writing samples. We also found that the critical thinking skills of the students instructed using the guided-inquiry based approach improve as they progress during the semester with guided-inquiry based instruction. Critical thinking skills of freshmen students receiving traditional instruction show a little improvement, and there is no change in critical thinking skills of advanced chemistry students during the semester.

Introduction

One of the goals of inquiry-based education is to develop the critical thinking skills of students. While critical thinking is embedded in classroom activities and in classroom materials geared towards providing inquiry- based instruction, it is an ongoing challenge for instructors to assess critical thinking abilities of students with traditional assessments like multiple choice exams or having students work on a traditional paper and pencil test. In a laboratory environment, oral discussion among students and the instructor provides some room to foster and simultaneously assess the critical thinking skills of students as a group. It is when the students do their individual writing component (such as in a laboratory report) that they display their individual thinking and reflective skills for a particular laboratory activity. In this study, a comparison is made between the laboratory reports of students who received traditional instruction during freshmen level college chemistry with students who received a guided-inquiry based Science Writing Heuristic approach in freshmen general chemistry. Senior level chemistry students' laboratory reports are also studied to understand the impact of traditional laboratory instruction and how it compares to guided-inquiry based instruction. The focus of this study is to evaluate the critical thinking skills of students using two different rubrics on critical thinking – *the York Technical College rubric (YTC) and the Hoyo rubric.*

The question arises why study critical thinking skills? What is the motivation? In many cases, research work is motivated by personal experiences and has a story behind it. This study is motivated by the frustration expressed by a postdoctoral teaching assistant who had taught freshmen level general chemistry laboratory at the Iowa State University using the guided-inquiry based Science Writing Heuristic approach and the following year was assigned to facilitate senior level inorganic chemistry laboratory in an instructor role, along with a co-teaching assistant and the instructor-in-charge of the laboratory. During a research group meeting towards the end of the semester, the postdoctoral assistant noted that in his observation the senior level chemistry students were not as effective as critical thinkers as freshmen students in laboratories using the SWH approach. The senior level chemistry students had poor writing skills that indicated ineffective critical thinking in their laboratory reports. This observation was taken as a challenge because senior level chemistry students have had more exposure to college chemistry and laboratory work and should be more adept at thinking and argumentation and should have better writing skills compared to college freshmen. For securing admission to Iowa State University, high school students are required to meet the Regent Index requirement for ACT/ SAT scores and must have completed the minimum required high school courses for the institution to which they apply. The Iowa State University requirement for natural sciences is three years of study of sciences at the high school level, with at least one year of study for any two disciplines including biology, chemistry and physics. This implies that students have an exposure to at least one year of high school chemistry before being accepted in the undergraduate science program at Iowa State University. Senior chemistry students have had more time to interact with the material and are expected to have advanced reasoning skills.

About the research Study

The present study is on the critical thinking skills of the students. Written work was evaluated to understand the differences in their critical thinking skills based on the student levels as freshmen and seniors, the instructional approach to which they were exposed, and how critical thinking compares across the groups during the semester.

A critical thinker is a person who can perform higher order thinking processes such as applying, analyzing, synthesizing and evaluating information or methods in a variety of situations. According to the National Science Education standards (33,145,175), student inquiry in the classroom covers a range of activities which provide a basis for observation, data collection, reflection, and analysis of firsthand experiences of students such as laboratory experiments or demonstrations. A successful science classroom involves collaboration of teachers and students in the pursuit of ideas where the students are engaged with an activity by formulating their questions and designing experiments to answer their questions, collecting data and representing the data and testing the reliability of their claim(s) with respect to the inquiry activity. Students in a collaborative environment explain to each other and learn from one another while justifying their observations and presenting evidence that supports their claim(s).

As stated in the content standards, students should be able to think critically and logically to make connections between evidence and explanations. What happens when students move out of the classroom environment and are no longer receiving any external guidance? Are students still applying critical thinking skills when writing their laboratory reports? Are they reflecting on the data as they did in the presence of their peers and the instructor? Do the laboratory reports of students who receive inquiry-based laboratory instruction display critical thinking abilities different from students who receive traditional laboratory instruction? Another aspect of critical thinking is a student's ability to analyze an argument by reviewing its relevance to established scientific knowledge, weighing the evidence and examining logic so as to decide which models and explanations are the best. Further, students should be able to review the data from experimentation, provide a summary of that data, and a logical argument about causal relationships deduced from the experiment. Students should be able to use scientific criteria to find a plausible explanation. Critical thinking involves decision-making about any anomalous data and how to account for it.

The Science Writing Heuristic approach has been used successfully over a decade to engage students in the laboratory and to improve student learning of scientific concepts and principles. The SWH process emphasizes knowledge construction by learning individually, collaboratively as a group, and using writing as a core practice to demonstrate student understanding. The Science Writing Heuristic is a framework that connects inquiry, argumentation, and language skills (Hand, 2008). The origins of the SWH as a guided-inquiry based instructional approach dates back to 1997 when Hand and Keys laid the foundation of a comprehensive tool that would capture the elements of the scientific method as a process of teaching and learning with scientific thinking embedded in the process and also as an outcome of the process. The Science Writing Heuristic is thus a tool or a problem solving device that enables the learner to structure their thoughts scientifically and conduct investigations in the laboratory much like as any scientist does.

The majority of students entering the freshmen chemistry lecture and laboratory come with a “plug and chug” mindset of learning chemistry. They want to apply an equation to get a final correct answer but, have little or no familiarity with experimentation in chemistry. These students have either witnessed experiments in the form of demonstrations by their instructors during high school or performed traditional verification laboratories using step-by-step directions to verify an idea laid out in the procedure. They completed fill-in-the-blank report forms to summarize results of their experiment. Given these conditions it becomes increasingly important to engage students in the thinking process and in preparing to conduct a chemistry laboratory activity effectively. Ideally any time that the students spend in contact with their peers and the instructor in a classroom or laboratory is the time to engage and interact with materials such as the textbook or laboratory equipment. While focusing on the subject matter they simultaneously discover principles, invent or introduce concepts while negotiating meaning collaboratively through observations, interpretation, analysis, and discussions. Although content skills and thinking skills are important, working in small teams or groups, learning how to divide work and share responsibility, collaborating, communicating and presentation are also a set of skills that students are expected to develop as a well-rounded learner. College is not merely a place for running from class to class to obtain a specified number of credits for a diploma with a grade point average ranging from acceptable to outstanding for the job market or higher education. The over-arching purpose of a college education is to prepare students as adaptable, scientifically literate, creative and thoughtful life-long learners who are professionals. Taking any course work and credits should thus contribute to this over-all goal. The intent of using the guided-inquiry based Science Writing Heuristic approach is thus to provide adaptive expertise to students at the beginning of their chemistry laboratory experience (helps them to be better critical thinkers across disciplines and over years). The skills they obtain in thinking and writing or the communication and team skills are not just limited to a chemistry lecture or laboratory setting only or only to that one semester time period.

In a traditional laboratory setting the instructor is in charge and directs students to complete the activities. Guided-inquiry based instruction provides enough guidance for students to safely use the materials in the laboratory while proposing questions for exploration as big ideas, hypothesizing about outcome, and deciding on experimental variables. The instructor carefully guides student thinking by first asking questions to ascertain their prior knowledge and then carefully scaffolding students to the laboratory activity, collect data, analyze and interpret the data/observations, and communicate their findings to their peers. Students work closely in such an environment and construct their understandings. In a traditional laboratory students may work individually or in pairs and leave the laboratory after collecting the data/ observations and having completed their part of the experiment without any interactions with peers and without sharing data/observations among groups. In a guided-inquiry based laboratory, pooling of observations and data on the chalkboard and in an Excel spreadsheet aids students in a) comparing their observations and data, b) finding patterns and anomalies, c) while at the same time being able to reach out to other groups/ teams in the class. The instructor acts as a facilitator and encourages students to make decisions about the questions they can explore with the materials available. Students are further able to decide how they can experiment safely, and in the given time, frame which experimental variables of a study can be explored. The role of an instructor is critical in a guided-inquiry based setting where a power shift occurs. The instructor is no longer the central authority figure; and the students as learners facilitated by an expert instructor are the key players in such a classroom. The instructor acts in such a way to promote higher order thinking skills while being open to student responses and aware of their prior knowledge levels. The Science Writing Heuristic approach successfully captures various elements of an effective guided-inquiry based laboratory approach.

The Science Writing Heuristic approach is strikingly different from traditional laboratory instruction in several ways. Key differences are summarized in Table 1.

Literature Review on Theoretical Frameworks and Critical Thinking

Assumptions from constructivism, critical theory of learning, and writing to learn science form the theory base of this study. Even though the learning theories merge at certain points, it is out of the scope of this chapter to touch on each of the constructs.

Table 1: Comparison of the SWH approach and Traditional laboratory instruction.

Traditional approach to laboratory instruction	SWH approach to laboratory instruction
Teacher-centered.	Learner–centered.
Emphasis is on technical skills and equipment handling while noting observations and collecting data (expecting what to look for, knowing when to stop the reaction, exact mass, precise set-up of experiment).	Emphasis is on conceptual understanding using materials available in the laboratory, stating a hypothesis, framing questions for experimentation, developing a procedure with some guidance and identifying the variables involved.
Instructor goes over the general procedure and conduct of laboratory literally spelling out for students all information regarding the experimental set-up, kind of data to be expected along with some observations (you will observe a green blue-flame when burning copper and you should get a 1:2 mole ratio for reacting copper (I) oxide with oxygen).	The instructor scaffolds student learning in the laboratory by asking questions that can be answered by experimentation, what variables are involved and how the experiment can be setup to answer the questions using the materials at hand.
Students have no input in the experimental design.	Student input is required for experimental design.
All the students have a common purpose.	Students explore different aspects of the activity (e.g., the relationship between density and mass keeping the volume constant and the relationship between density and volume keeping the mass constant).
Concepts are introduced in the beginning of the laboratory write up.	Concepts are introduced by the instructor based on patterns in data and observations and do not appear explicitly in the laboratory experiment write up.
Students work individually or in pairs.	Students work in small groups of 3-4 students per group.
Students collect individual data and observations in the laboratory notebook.	Students collect their data as a group and share their observations, data and findings with other groups in class on the chalkboard and in Excel spreadsheets.
Student-student interaction about the activity is minimal.	Student to student interaction on the activity is frequent.
Requires students to just focus on the write up based on the questions that can be answered from the information provided in the write-up or by looking at some observations or the data collected individually or in pairs.	Enables students to use knowledge acquired from the lecture if the lectures happen before the laboratory activity or the activity leads to transfer of knowledge to solving problems in the lecture component of general chemistry if the laboratory activity comes before the lecture.
Limits students to the data and observations they have collected individually and may lead to an incorrect interpretation, hence more misconceptions.	Requires students to share data and observations and discuss within groups and among groups at the end of the laboratory to compare their findings with that of other groups and look at trends and anomalies (further analysis of the findings).
Students make their conclusions based on their findings.	Students are required to use references other than the laboratory book such as peer-reviewed literature, the course text book, and the Internet and actually cite their references. Further reading is encouraged to critically analyze the group data and class data and reflect on the understanding achieved as a result of the activity.

Hence the characteristics of constructivism, critical theory, and writing to learn science will be discussed in detail, present study will be examined mainly using these three lenses, with the understanding that other constructs may have a subtle role, too.

From Piaget to Constructivist theory

Jean Piaget, a Swiss psychologist, was a pioneer in the epistemological sciences who studied the human learning process. Piaget made observations on how children learn when negotiating their understanding of the world through assimilation, accommodation and equilibration. During the period from the late 18th to the early 19th century, two schools of thought existed for human knowledge acquisition-*empiricism and nativism.* According to the empiricist view, all knowledge is obtained through sensory experience, whereas nativists hold the view that knowledge is inherent and arises from within humans. Piaget argued that for something to be considered a stimulus there has to be some mental representation that is followed by the proper assimilation of a stimulus. Thus a behavior is acceptable until it meets its contradiction and the process of assimilation follows. Piaget was influenced by the German philosopher Immanuel Kant, who viewed knowledge acquisition as a complex process of interaction between the sensory imprint of things, or rational constructs that are independent of any experience. In Piagetian terms, assimilation is defined as a process during which new information is perceived by an individual with reference to existing schemas or mental structures. Assimilation is useful when there is some pre-existing framework that allows an individual mind to compare new information and assimilate it, based on that existing framework, to apply it further actively (Lawson, 1997). Assimilation is followed by accommodation during which an individual undergoes a change in schema so as to fit the reality. The stage of equilibration involves both assimilation and accommodation to create new mental structures and replace the old ones or accommodation of the new structures with reference to the existing cognitive structures. The central point of Piaget's theory is focused on the structure rather than content – how the mind works as opposed to what it does. It emphasizes the process of understanding and, to an extent, ignores the role of prediction and control of behavior. Piaget's theory of cognitive development revolutionized understanding of human learning and lead to several theoretical frameworks. Piaget's theory of cognitive development is neither nativist nor empiricist as some critics may call it, but it tends to be more interactionist or constructivist as it connects human development (an internal growth process) and its response to external experiences. This leads to a cycle of assimilation, accommodation, and equilibration. An individual's response to a problem or a given situation depends on his/her sensory input/reception at that instance and on the intermediate cognitive processes that cause extension of the understanding of the experience/situation for the individual. In addition it offers newer possibilities to respond, leading to "*adaptive intelligence*". According to Piaget, there are four main periods of human cognitive development (a) sensorimotor, from ~0-2 years; (b) preoperational, from ~2years-7 years; (c) concrete operational, from ~7 years-11 years and (d) formal operational, from ~11 years-15 years (Philips, Jr., 1923; Herron, 1975). During the first stage of cognition, a child acquires much of his learning through sensory-motor experience in which knowledge of the world is limited to sensorimotor functions of touching, tasting, seeing, and hearing. During this period, children learn by holding objects, listening to sounds, sucking on objects, and gazing. During the pre-operational period, a child undergoes significant development in language skills and general symbols of representation, pretend play, and can mimic adult behavior to some extent (calling names of parents by listening to grandparents or friends of parents), but have very little to no reasoning skills. The third stage, concrete operational, is characterized by the development of reasoning abilities. Children develop a sense of mental activities and are able to think logically based on their concrete experiences, but their intuitive skills and abstract abilities remain undeveloped. Based on concrete experiences the children are able to build logic, yet struggle to think deductively, hypothesize, or do abstract reasoning. The last stage is the formal operational stage of cognition. At this stage, mental faculties undergo significant development. From this stage onto adulthood (theoretically), reasoning is well developed, there is an increased ability to organize information, and people can understand abstract concepts and engage in deductive thinking and methodical problem solving. In the formal operational stage, students begin to see various possibilities and are able to consider all the options for a given scenario. Based on the Piagetian approach, students receiving college chemistry instruction should have well-developed formal operational thinking and should be able to express their ideas clearly and coherently in their written work. However while a concrete student may be able to understand some parts of advanced concepts, it is hard for a student at the concrete stage to understand certain concepts fully that require the formal operational stage (Lawson, 1975). For understanding abstract ideas such as stoichiometry which requires formal thought, a dimensional analysis approach has been used successfully with students who are still at the concrete thinking level. Herron (1975) suggests presenting abstract chemistry concepts that require formal thought in a way that students are able to understand the chemistry behind the concepts. Chemistry is a formal science by its nature and so becomes important to develop the formal thinking abilities of students in this discipline by providing concrete learning experiences to students. Herron adds that just concrete experiences cannot lead to learning unless accompanied by critical thinking on the part of students which is seen lacking in traditional laboratory work and helps least in terms of learning. In Herron's words (1975)

> "Inclusion of concrete experiences –i.e. opportunities to actually touch, smell, see and manipulate materials that would lead to the concepts appears to be important. But concrete experiences are not particularly useful if all that a student does is touch, smell, see and manipulate without being forced to think about what he is doing. Because this is what happens in most of the lab work, it does little good. It would appear that those educational experiences which encourage the intellectual debate of ideas, the weighing of evidence and an emphasis on "making sense" out of observed facts are ones that lead to the development of formal thought. But these educational experiences are time consuming, require a great deal of interaction among students or between teacher and student and are painfully frustrating for both the student and the teacher. …because we limit our instruction to that which requires rote memory, students are never forced to develop their thinking to the level of formal thought, they cannot understand the abstract material we present."

According to Herron, when instruction is provided at an abstract level and students are tested for recall of facts and use of algorithms, we barely challenge students to think about the *what, how* and *why* in chemistry. There is a lack of interaction between the instructor, content being presented, and the learner(s) which also is reflected in student laboratory work. Instructors have to create a situation in which the prior knowledge and beliefs of students entering the chemistry laboratory or classroom are challenged and tested conscientiously by engaging them in activities that promote critical thinking through observation, data collection, generalizations, debate and discussion. It is important for instructors to know whether the students can develop scientific arguments, solve a problem using different approaches, draw comparisons via observation and analysis, and use rational thought. There are numerous opportunities for instructors to gauge student thinking skills. If the instructor understands the characteristics of informal and concrete thinking and genuinely attempts to understand how students arrive at solutions to the problems posited to them, it is possible for instructors to delve deeply into the student thinking processes via during informal contact during the laboratory and by way of laboratory reports, responses to essay questions, homework problems, and informal class discussions (Herron, 1978).

Constructivism

Piaget's theory led to many schools of thought and several learning theories emerged. Some schools of thought developed in an attempt to contradict Piaget and some other theories (constructivism, social learning theory, and the learning cycle approach) were built on his ideas of learning as an outcome of the interaction of a series of complex physical and biological processes.

Piaget's theory pinpoints that cognitive development takes place in an individual simultaneously with the physiological development of the brain. As an individual grows physically, the ability to make sense of physical experiences and abstraction develops too. Constructivism as a learning theory has been influenced by the work of John Dewey, Jean Piaget, Ernst Von Glasserfeld, Lev Vygotsky, among others. Constructivists believe knowledge to be emergent, developmental, nonobjective, viable, constructed explanations by humans who actively engage in the meaning-making process in socially and culturally discursive communities. From the constructivist standpoint, learning is a self-regulated process which is accompanied by an ongoing battle between personal representations of the world and the discrepant events that bring forth new representations of reality based on insights leading to a venture of constructing and reconstructing reality. The meaning-making process is aided by cultural and sociological heuristics and involves negotiation through discursive learning in cooperative/collaborative communities of practice. Constructivism stands in opposition to the more traditional classroom and laboratory practice of transfer of knowledge from the instructor to learner, verification of facts, memorization of symbols and attaining unmatched subskills. According to the constructivist theory of learning students should be provided adequate opportunities to gain concrete experiences, to construct meaning, seek patterns, pose questions, build upon their ideas, develop strategies, debate and defend their ideas, draw conclusions, and to re-develop their questions (Fosnot, 2005). A classroom dynamic in which learners share, discuss, debate, and develop their understandings from one another challenges the autocratic position of the instructor. Learners gradually and subtly take charge of their learning, own their thought process and feel empowered.

Critical Theory and Critical Thinking

A major goal of any scientific educational undertaking is to develop the critical thinking skills of the people involved. Weil and Anderson (2000) argue that educational opportunities should seek and develop the critical capacities in the interests of learners by not merely translating reality but transforming it. Laboratory instruction aims at providing students with thinking skills in addition to technical skills. However the traditional approach to laboratory produces more technicians and fewer critical thinkers.

Instruction aimed at developing the critical thinking skills of students (including a metacognitive understanding of critical thinking) requires an instructor to be capable of a post-Piagetian, meta-analytical form of cognition in relation to various disciplines and forms of knowledge (Kincheloe,2000). Kincheloe (1998) describes post-Piagetian or post-formal thinking as a self-reflective form of thinking that attempts to move beyond the logical base of Piagetian formalism by taking a distant approach to subjugated ways of knowing using critical theory, and postmodernist critique. Post-formal instructors are researcher-teachers who are self-critical of their own thinking as they teach critical thinking skills to their students. Thus it is hard to determine any boundaries when it comes to thinking and levels of cognition. Adult cognition in a post-modern world is not limited to formal operational development. When properly implemented by an instructor and a group of students, inquiry-based laboratory instruction attempts to promote the critical thinking skills of students. The activities in these laboratories are designed using a learning cycle approach in order to provide opportunities to explore, invent, and apply the concepts. Students conduct laboratory activities in groups, generate data as a class, and negotiate their understanding of a concept as a group. This promotes individual critical thinking and reflection along with peers and the instructor. Students in inquiry–based laboratories are also expected to present their understandings in an organized way in the form of a written laboratory report. This product is the individual component of laboratory work and is an overview of the experimental work performed and a student's reflection of group and individual learning from the activity. Critical thinking is commonly unheard of in chemistry classrooms taking a traditional approach (which reflects a lack of student engagement with the topic and the laboratory activities). The technical format of a traditional laboratory curriculum limits the critical thinking abilities of students as it systematically breaks down the information into small chunks that can be easily digested and regurgitated on tests or laboratory reports. Macedo (1994) suggests that the technical structure of a curriculum that emphasizes prescribed factual learning with an aim to perform on standardized tests disconnects the learners from the events in their lives. This will only reduce critical thinking instead of enlightening students. Learners and learning are connected to each other and cannot be viewed as independent from one another. Kincheloe asserts that a linear approach to learning has too many problems at the superficial level when deeply assessed. Students learn fragmented bits of curriculum and isolated sub-skills that reflects in their written work. When laboratories focus too much on procedural skill and less on engaging students in thinking, it leads to the development of what the epistemologists refer to as “uncritical–critical thinking”. Uncritical–critical thinkers accept the status quo and fail to question dominant practices. This is especially common in the sciences where the teacher or the laboratory instructor is seen as the source of knowledge and any word emerging from the mouth of the instructor is accepted as unquestioned truth. Students passively take down notes and instructions for performing experiments. They blindly follow a recipe to come to the prescribed conclusions. Where is the critical thinking in this kind of environment where students are given everything they need to pass the class and secure a grade? When students and teachers are not confronted to think about the context and the relevance of an experimental activity they gain little insight into the forces that shape their understandings and their awareness (Kincheloe, 2000).

Kincheloe and Steinberg (1998) critique scientific thinking calling it the highest expression of formality by the advocates of uncritical-critical thinking. Some scholars have been resistant to their limitations of formal thinking. They reduce thinking to micrological skills that are often taught as a fragmented vision of scientific thinking that teaches students to differentiate, group, to identify common properties, to label, categorize, distinguish relevant from irrelevant, relate two points, infer, and explain their understanding. Scientific thinking is viewed as hyper-rational and obtrusive to reflective practice. Post-modernists argue that rational, accurate thinking emerging from modernism’s one-truth epistemology results in producing a group of right-answer givers and timid recipe followers. Taking a critical constructivist position, it can be argued that Piaget’s work did not limit learning to formal operational development as interpreted by critical theorists. Rather, Piaget’s work on intellectual development lead educational theorists to construe the role of the instructor as a guide to learning, someone who facilitates the *development* of learning instead of dispensing information and being an authority. This hints towards critical thinking and critical reflection on the part of the learner as guided by the instructor, who also engages in critical self reflection about knowledge and learning. Piaget was a genetic epistemologist and he occasionally commented on education. As Duckworth quotes Piaget in *Piaget Rediscovered* (1964):

> "The goal in education is not to increase the amount of knowledge but to create the possibilities for a child to invent and discover. When we teach too fast, we keep the child from inventing and discovering himself. Teaching means creating situations where structures can be discovered; it does not mean transmitting structures which may be assimilated at nothing other than verbal level."

In his work, Piaget did not study the implications of learning theories for modern education; he worked to unravel the development of human cognition. Based on several studies (Lovell, 1961; Dale, 1970; (McKinnon, 1971) Herron (1975), in *Piaget for Chemists,* argues that a majority of students do not reach the formal operational stage of thinking outlined in Piaget's developmental theory. The question that arises from the previously mentioned studies is about the nature of instruction that was provided to students and the level of scaffolding in these classrooms. It can also be analogically argued that if you provide a square to a blind person and keep explaining that it is a rectangle without teaching the concept of the equality of sides (measurement and what it means to say equal), and when the blind person has a surgical sight recovery, he or she would still perceive a rectangle as a square based on the prior sensory experiences. So the Piagetian concept and constructivist ideas are relevant to learning, but from a critical standpoint, the instruction cannot be tailored as one- size-fits-all when there are diverse learners with a diverse set of skills in the laboratory. Herron posits that chemistry educators need to reconstruct the teaching of chemical sciences and work with students on the basis of the skills and knowledge they bring to the activity and not from the objective and pragmatic standpoint of science that leads to the notion of the instructor being the means and end of all scientific knowledge in a classroom or laboratory. Concrete experiences are helpful in meaning making, but simply assuming that a concrete laboratory experience requires no formal thinking is dangerous (Piaget, 1978). At the same time, captiously looking from a critical thinking perspective, one can disagree with what the "critical-critical thinking" research says about the nature of scientific inquiry. The premise is that "critical-critical theory" is looking at learning in sciences with a reductionist view, assuming that the scientific method is flawed, being limited to formal operational processes. By critically looking at Piaget's theory of cognitive development, the processes of assimilation, accommodation and equilibrium and reconstruction of knowledge are active and ongoing processes on the part of an individual. Interaction with self and with the environment plays a key role in this development. Theorists have not isolated physical reality from physiological development. Piaget and other constructivist theorists in their quest for human learning and the process of knowledge acquisition have continuously questioned the epistemology and added layers to the science of learning and knowledge creation. The point with respect to the present research study is - do chemistry students understand how to use their critical thinking skills? Are they aware of their own thinking? Do they about think what they write in scientific reports? Is there an approach that can teach them how to think?

Development of critical thinking skills is a rigorous process. The question is how do instructional approaches lead to a formal/informal development of critical thinking? Acquisition of critical thinking is jeopardized by the very people who need it most. Students are resistant to instruction that demands that they think. Instructors shy away from teaching critical thinking skills to students because of assessment issues, as it is hard to measure and quantify. Critical thinking is important in education. Whether it is applied or not depends on the purpose of the instruction. If the purpose is to provide factual information to students and memorization of symbols and formulas, then rote learning would suffice. If the instructional objective is to develop the logical skills of students to enable them to make informed and rational decisions, then development and application of critical thinking skills is central as a process and product of learning (Kurfiss, 1988).

Writing to Learn Science and the Science Writing Heuristic

Research on the Science Writing Heuristic (SWH) approach, as an alternative format to teaching was undertaken by Hand, Prain and Collins (1999). The SWH approach was used as a novel tool for learning in the laboratory from various activities at the secondary science level. As a result of this research, the SWH approach emerged as a framework for teachers for designing guided–inquiry based classroom activities. At the same time the SWH approach can be used for students as a format for report writing and understanding the nature of science while generating meaning from data, making connections between the procedure and the activity at hand, making claim(s), and building evidence and to metacognitively interact with the content and activity. The construction of knowledge through collaborative peer discussion and writing to learn science formed the basis of the Science Writing Heuristic approach. Such connections according to Hand (1999) may not be apparent to students initially but may eventually become a usual practice in learning science.

The Science Writing Heuristic approach provides a template for students and a template for instructors. The instructor template includes a range of activities for the laboratory aimed at engaging students in thinking meaningfully via reading, writing, and sharing ideas through discussions about the concepts. Teachers are in charge of using the template based on their need, the activities on which they want to focus during the semester, and designing questions that parallel the investigations intended for a given topic of study. The teacher template can thus be implemented effectively to elicit students' prior knowledge using concept maps before conducting the actual activity in the laboratory. This may lead to a pre-laboratory discussion during which students engage in informal writing, brain-storming, and proposing questions. The pre-laboratory session further opens the door for conducting the laboratory while making observations and collecting the data as a group.

The next stage in the teacher template is to lead students into the negotiation phase. The first level of the negotiation stage requires the students to write their individual understandings based on the experimentation. The second level of the negotiation phase involves students in data sharing and comparison, while searching for trends and anomalies as a group. In the third phase of negotiation the instructor's role is to encourage students to further advance their ideas by comparing them to textbooks, literature, or peer-reviewed resources (online or in print). The fourth and the final phase in negotiation, requires the students to metacognitively reflect on their ideas from the pre-experiment or concept mapping stage to the reading and comparing stage in order to summarize their thoughts in writing, developing newer concept-maps.

The student template for the Science Writing Heuristic approach primarily involves using experimentation, data and observations, and the negotiation phase to engage students in a thought process to develop viable explanations along with their peers to make knowledge claims. Students start from the specific and move to a generalization stage by comparing their data and observations to a pooled class data set while debating on the evidence in support of their claims. The student template provides a platform for learners to understand the tentativeness of science and that scientific ideas have to be tested, debated, and proven before being accepted by the scientific community. Students reflect on their prior ideas before the activity and shift in their ideas as a result of collaborative negotiation, reading, and referencing.

The Science Writing Heuristic approach was used in a second-semester college level general chemistry laboratory curriculum for activities related to the concept of “equilibrium” (Greenbowe and Rudd, 2001). Students using the Science Writing Heuristic approach showed better learning on lecture exams, laboratory practical exams, and an improved understanding of the principles of equilibrium processes in their laboratory reports and lecture exams when compared to students using a traditional verification approach and report writing format.

Purpose of the study

Prior research on analysis of student laboratory reports has emphasis on the structure and quality of student arguments. Some researchers have developed inquiry-based laboratory activities with an emphasis on the written component to promote student conceptual understanding of science. Prior research has also shown the students receiving inquiry-based instruction present better scientific argumentation as compared to students doing verification laboratories. The present research study extends the research to compare the critical thinking skills based on the written laboratory reports of (a) students who take a more rigorous one-semester survey of general chemistry (for engineering majors only) to (b) students who take the first semester of general chemistry (all other science & engineering majors) and (c) advanced level chemistry/chemical engineering majors. The purpose is to understand the impact of the laboratory instructional approach on the critical thinking skills of students via their laboratory report work as well as to study whether the student written work provides any evidence of improvement in critical thinking during the course of a semester.

Research Hypothesis and Research Question(s)

It is hypothesized that the instructional approach does not impact student writing skills. Students in guided inquiry-based laboratories have similar critical thinking skills in specific chemistry areas as students at the senior level who engage in traditional laboratory work. The alternative hypothesis is that students' critical thinking varies with the instructional approach used, the numbers of years of chemistry experience students have, and the courses in which students are enrolled during the semester. Based on the research hypothesis the following research questions are proposed:

1. Are the students experiencing guided–inquiry instruction in the laboratory better critical thinkers than those students who instead use a more traditional approach?
2. Is there a difference in the critical thinking scores for student laboratory reports in (a) freshmen level versus advanced level of chemistry laboratory and (b) for student reports in different chemistry courses (167L, 177L, and 401L), and c) the time of the semester (first month, second month and third month) from which the reports are drawn?
3. What is the correlation between two rubrics on student reports for critical thinking mean scores?
4. Is there any interaction between (a) course and time of the semester from which the laboratory reports were drawn, or (b) the instructional approach (treatment) used and the time of the semester from which the reports are drawn for the study?

Research Method

This is a quasi-experimental quantitative study like most educational research studies in which the assignment of participants to the instructional approaches or levels was not by chance (Cohen, 1980). Students sign up for a course of study during a given semester based on their program structure. In general, all the laboratory students in the chemistry 177 course are instructed using the Science Writing Heuristic approach and nearly 800 students sign up for both the lecture and the laboratory component of this course. Effective implementation of the Science Writing Heuristic approach depends on the training, experience, and willingness of the teaching assistants assigned to the course. The outcome of each laboratory activity depends on the beginning questions of the students and the facilitation of the instructor. The instructor facilitates the student discussion of beginning questions at the end of which they determine a class question that is testable by experimentation. In 167L and 401L students are instructed using the traditional method and the format of instruction is similar among all the teaching assistants. The outcome of the laboratory activity is known to the students as well as the instructor as it is provided in the laboratory write-up.

Setting

This study took place in a midwestern university in three undergraduate-level chemistry courses that were taught using two different instructional approaches. In two of the courses, the students received traditional laboratory instruction and in the third course students were instructed using the guided-inquiry based Science Writing Heuristic approach. Out of the two chemistry courses that received traditional laboratory based instruction, one course had freshmen students (167L). The other course was an advanced inorganic chemistry laboratory course (401L) for chemistry seniors and chemical engineering majors. The course in which guided–inquiry based instruction was used was comprised primarily of freshmen general chemistry students with science and chemical engineering majors (177L). The advanced chemistry 401L course had an enrollment of 12 students out of which 11 students completed the course. The general chemistry course for college freshmen engineering majors (chemistry167L) had 158 students who completed the course. The general chemistry course for science and chemical engineering majors (chemistry 177L) had 562 students who completed the course.

The Chemistry Laboratory: Overview of the Three Courses in the Study

Chemistry 167L is a laboratory course for engineering students. Students are required to have concurrent credits for general chemistry 167 or the students must have completed general chemistry 167 credits to be eligible for chemistry 167 laboratory. General chemistry 167 is an accelerated course designed for students with an excellent preparation in math and science. It is a terminal course for engineering students who do not plan to take additional courses in chemistry. Chemistry 167 laboratories meet once every week during the semester. A laboratory section for chemistry 167 may have one to two teaching assistants at a time. The number of teaching assistants in a given laboratory depends on the capacity. A larger laboratory can hold up to a maximum 40 students and has two teaching assistants. Smaller laboratories can hold a maximum of 20 students and have one teaching assistant. The general ratio in these laboratories is approximately 18 students to one teaching assistant. The laboratory manual used for Chemistry 167 has thirty experiments out of which students perform 13 experiments in a given semester. The students in this study were also enrolled in the lecture component of Chemistry 167. There is some coordination between the lecture and the laboratory as evident from the summary of the lecture and laboratory components of Chemistry 167 in Table 2.

Table2: Summary of general chemistry for engineers (Chem 167 and 167L).

	Chem 167	Chem 167L
	Two instructors for lecture component	Instructor in charge and multiple TAs as laboratory instructors
Week 1	Intro - Atoms & Molecules	Measurements
Week 2	Molecules, Reactions and Chemical Equations	Observing Chemical Reactions
Week 3:	Stoichiometry	Polymers
Week 4:	Stoichiometry and Gases	Empirical Formula of an Oxide of Copper (Appendix G).
Week 5:	Gases	Gas Phase Chemical Reactions
Week 6:	Periodic Table and Atomic Structure	Atomic Spectroscopy
Week 7:	Chemical Bonding	Phase Diagram for the Bismuth-Tin System
Week 8:	Chemical Bonding and Molecules and Materials	Optical Diffraction Experiments
Week 9:	Molecules and Materials and Energy	Heat of Formation of Magnesium Oxide
Week 10:	Energy and Chemistry	Oxidation Reduction Reactions
Week 11:	Thermodynamics	Kinetics
Week 12:	Kinetics	Equilibrium
Week 13:	Kinetics & Equilibrium	Electrochemistry of Galvanic Cells
Week 14:	Chemical Equilibrium	
Week 15:	Electrochemistry	

The students in the lecture component of Chemistry 167 take four hour exams and a final exam. The students in the laboratory component of Chemistry 167L have four laboratory practical tasks related to the laboratory activities during the semester. The instructors in the two sections of the lecture covered similar content with the exception for the second instructor who also covered some aspects of nuclear chemistry at the end of the semester. Thus students enrolled in the laboratory covered similar content during the lecture. Being in the laboratory course which had the same instructor but different teaching assistants for different laboratory sections, students did similar laboratory activities and they were tested on similar laboratory tasks on the laboratory practical exams.

Science and engineering majors enroll in general Chemistry 177 accompanied by 177L. Students enrolled in the lecture component must enroll for the laboratory component of the course. Chemistry 177 is the first semester course of a two semester sequence which explores chemistry at a greater depth than chemistry 167. The emphasis of chemistry177 is on concepts, problems, and calculations. The course is mainly designed for physical and biological science majors, chemical engineering majors, and all others intending to take 300-level chemistry courses. The laboratory component of the course is conducted by teaching assistants under the supervision of the professor in charge of the course. There is one teaching assistant per 20 student laboratory section. Laboratory experiments and lectures were closely integrated. Depending on the pace, a topic was first covered in the laboratory and then in depth during lecture or vice-versa. Table 3 displays a tentative summary for chemistry 177 and 177L during a given semester.

Advanced chemistry students take an advanced inorganic chemistry laboratory Chemistry 401L. Chemistry 301 is a pre-requisite that covers the theoretical basis for advanced inorganic concepts Chemistry 401L. As compared to Chemistry 167L and Chemistry 177L, students have a pre-requisite one year of high school chemistry and 1 year of high school mathematics or the equivalent. Students who enroll in Chemistry 401L have had four years of chemistry background with at least one year of high school chemistry and three years of college chemistry. Table 4 displays a typical B.S. chemistry study plan indicating the number of chemistry credits advanced chemistry students may have acquired prior to a 400 level laboratory class.

Table3: Summary of general chemistry 177 and 177L.

	General Chemistry I (chemistry 177)	General Chemistry Laboratory(Chemistry 177L)
	Three instructors and three different lecture sections	One teaching assistant per laboratory section under the supervision of the professor in charge
Week 1	Matter & Measurement	Mystery Event: Introduction to the Science Writing Heuristic Approach; Data Collection on Properties of Soda Pop
Week 2	Atoms, Molecules, and Ions	Analysis of a Mixture
Week 3	Atoms, Molecules, and Ions; Stoichiometry	Chemical Reactions and Identification of a chemical compound (Appendix F).
Week 4	Stoichiometry	The Reaction of Zinc and Iodine
Week 5 and 6	Aqueous Reactions and Solution Stoichiometry	Interactions of Acids and Bases
Week 7and 8	Thermochemistry	Investigating heat exchange in Physical Processes; Investigating Heat Exchange in Chemical Processes
Week 9	Periodic Properties of Elements	Reactions of Several Elements; Reactivity of Metals
Week 10	Periodic Properties of Elements	Reactions of Several Elements; Reactivity of Metals (continued)
Week 11	Chemical Bonding	Spectrophotometric Analysis
Week 12	Molecular Geometry	Molecules and Ions
Week 13	Molecular Geometry; Gases	Alka-Seltzer: An Application of Gas Laws
Week 14	Gases	Lab Practical Exams
Week 15	Intermolecular Forces: Liquids and Solids	Lab Check Out

Table 4: Sample study plan at Iowa State University (2009–2011 catalog) for B.S. chemistry.

Degree	Semester	Courses	Courses
B.S. in Chemistry Required Courses 86.5 credits	1	Chem 177 Gen Chem 4 credits	Chem 177 Lab 1 credit
	2	Chem 178 Gen Chem 3 credits	Chem 211 Quant . Analysis 2 credits
	3	Chem 331 Organic Chem 3 credits	Chem 333L Lab 2 credits
	4	Chem 332 Organic Chem 3 credits	Chem 334L Lab 2 credits
	5	Chem 324 Quantum Mechanics 3 credits	Chem 316 Instrumental Analysis 2 credits
	6	Chem 325 Chem Thermo 3 credits	Chem 322L Lab 3 credits
	7	Chem 401L Inorganic Lab 1 credit	Chem 402 Inorganic Chem. 3 credits

Students in Chemistry 401L perform experiments that build on the prior knowledge of general, organic and analytical chemistry. The concepts taught in general chemistry (either

Chemistry 177 or 167) are applicable in Chemistry 401L. Inorganic chemistry 401L course is mainly focused on the preparation and characterization of inorganic and organometallic compounds by modern techniques. Chemistry 401 L is intended for students majoring in chemistry or biochemistry.

About the Chemistry 401 Laboratory:

Students in the Chemistry 401L course are required to complete nine experiments at the rate of about two experiments every three weeks during the semester and have 14 weeks to complete the course in addition to laboratory check in and check out. Students have three required experiments and they can make a choice among the experiments from Group 1 to Group 3 experiments as outlined in the syllabus in Table 5. Students were instructed using a traditional approach and there were three instructors present during each laboratory meeting for the 11 students who enrolled. The laboratory text provides students with detailed procedures and a theory based for each activity. A typical structure of Chemistry 401L is as shown in Table 5 and the required laboratory report format for the course is summarized in Table 6.

Study participants

The participants in this study were college freshmen enrolled in general Chemistry 167L (N=10), Chemistry 177L (N=10), and advanced inorganic Chemistry 401L (N=10). Table 8 gives an overview of the courses in the study as well as the instructional approach used in each of the three courses. For chemistry 167L all the participants were males; four out of ten participants were females for Chemistry 177L and one out of ten participants was a female for Chemistry 401L.

Table 5: Structure of 401L (1 period = 4 hours).

Required Experiments:		Post Lab Questions	Lab Periods
Week 4	Handout C: Preparation of $(CH_3)_3CNH_2{:}BH_3$). (Appendix H).	3, 6, 7, 8	1
Week 11 & 12	Handout D**:** Preparation and Use of a Titanium Metallocene.	1, 2, 3	1
Group 1 Experiments (Choose 3 out of 7):			
Handout A	Job' Method.	1, 2, 3, 4	1.5
Expt. 10	Ion Exchange Separation of Ionic Complexes.	1, 4, 6, 7	2
Expt. 11	Metal-Metal Quadruple Bond	1, 2, 3, 4	2
Expt. 12	The Magnetic Susceptibility of $Mn(acac)_3$.	2, 3, 4, 9	1.5
Expt. 13a	Synthesis of Co(III) Complexes.	2, 3, 7	2
Expt. 13b	Aquation of $[Co(NH_3)_5Cl]^{2+}$.	3, 4, 5, 6	1
Expt. 14	Optical Isomers of $Co(en)_3{}^{3+}$.	2, 6, 7	2 – 3
Group 2 Experiments (Choose 1 out of 3):			
Expt. 1	Preparation of $YBa_2Cu_3O_7$.	1, 2, 3, 4	2 – 3
Expt. 2	Preparation of $VOPO_4(H_2O)_2$ and $VO(HPO_4)(H_2O)_{0.5}$.	1, 2, 3, 4	2 – 3
Expt. 8	Preparation of $Ph_2PCH_2CH_2PPh_2$ (DPPE); $Ni(DPPE)Cl_2$.	1, 2, 3, 4	2
Group 3 Experiments (Choose 2 out of 3):			
Expt. 21	Cobaloximes: Models of Vitamin B12.	1, 3, 4	1.5
Expt. 23	Tetraphenylporphyrin and its Cu(II) Complex.	1, 5, 6, 7	1 – 2
Handout B	Chromatography of Ferrocene Derivatives.	1, 2, 3, 4	2
Week 13 & 14	Independent Project		2 – 3

The key differences between the traditional laboratory report writing format and the Science Writing Heuristic report format are summarized in Table 7.

Table 6: Laboratory report format for chemistry 401L.

1.	Purpose	a) A short statement identifying the goal of the experiment and how the goal of the experiment is to be approached b) Indicate important criteria/evidence for success.
2.	Procedure	a) Do NOT copy the instructions in the lab manual. b) Write a brief step-by-step account. c) Include balanced chemical equations for each reaction d) Report all observations
3.	Data	a) A copy of pages of your laboratory notebook. b) Data table. c) Show sample calculations.
4.	Spectra	a) Title; assignments for the important peaks; b) Organize peak positions, assignments, and Literature values into a table. c) Name, date, experiment #, compound, solvent, parameters, etc.
5.	Discussion	a) Results b) Procedure c) Calculations d) Literature
6.	Conclusion	a) Based on goals and results
7.	Assigned Questions	a) Answer only the questions required on the course syllabus. b) Refer to inorganic chemistry textbook; analytical chemistry textbook; and references for each experiment in your inorganic laboratory textbook.
8.	References	Any additional references

Table 7: Difference between SWH and traditional reports.

Standard Report Format	SWH Report Format
1. Title, purpose (aim)	1. Beginning questions—What are my questions? (Big idea)
2. Outline procedure	2. Tests and safety-What will I do? How will I stay safe?
3. Data and observations	3. Data, Observations, Calculations, and Graphs—What can I see? What data will I collect?
4. Balanced equations, calculations, graphs, charts	4. Claims—What can I claim?
5. Results	5. Evidence and Analysis: How do I know what I know? What patterns do I see? Why am I making these claims?
6. Discussion	6. Reading and Reflection: How do my ideas compare with others' ideas (peers, text, instructor, literature). What are some sources of error? How does the activity tie to the big idea? How have my ideas changed?
7. Conclusion(s)	7. Post-lab question(s): How can I apply my ideas further?

Table 8: Overview of the study.

CHEM 177L	CHEM 167 L	CHEM 401 L
General Chemistry I	General Chemistry	Advanced Inorganic Chemistry
Freshmen	Freshmen	Seniors
Science and Chemical Engineering majors	Engineering majors	Chemistry and Biochemistry majors
SWH based-1 TA per lab section meeting. 1 lab meeting per week for a duration of 3 hours	Traditional- 2 TAs per lab section meeting. 1 lab meeting per week for a duration of 3 hours	Traditional – 2 TAs and an instructor per lab meeting. 1 lab meeting per week for duration of 4 hours.

Data Collection

Student laboratory reports produced by the SWH-based approach for chemistry 177L were collected for a semester. Similarly laboratory reports were also collected for chemistry 167L in which traditional laboratory instruction and format were used. Student scores on the laboratory tasks and laboratory practical exams were collected for Chemistry 177L and Chemistry 167L. The laboratory reports selected for Chemistry 177L and Chemistry 167L were about stoichiometry, chemical reactions, and thermochemistry. Laboratory reports selected in the study for Chemistry 401L were about synthesis and characterization of inorganic compounds in which stoichiometry and concepts of bonding were involved. Printed reports for Chemistry 401L students were scanned and their scores on all laboratory reports and on their end of semester independent projects were collected.

Data Analysis

For the purpose of data analysis, the laboratory report scores for the first laboratory activity were used for the baseline comparison of the three groups in which two different instructional approaches were used. Laboratory reports were evaluated for ten students for each course in the study. Three laboratory reports were selected per student for each of the three courses making a total number of ninety laboratory reports evaluated. The laboratory reports were selected for activities that were done early in the semester, at the middle of the semester, and towards the end of the semester. Thus there are three different time zones for the laboratory activities – an activity for the first month; an activity done in the second month and an activity that was done in the third month of the semester. For evaluating the critical thinking skills demonstrated in the laboratory reports two rubrics were used to. The stages of critical thinking displayed in the laboratory reports were scored independently by two chemical education researchers based on (a) a rubric developed by Maria Oliver-Hoyo (2003) and (b) a rubric developed at The York Technical College (2004). Inter-rater reliability was established by scoring six laboratory reports per course (18/90 reports in the study). Three laboratory reports were selected per student for each course. All the identifiers were removed from the laboratory reports. The laboratory reports were typed into a rich text document, coded and scored for cognitive traits based on (a) the Hoyo rubric followed by (b) the YTC critical thinking rubric. The frequency distributions for the traits were plotted using JMP 9.0 software. The scores obtained on each trait were then totaled and scaled to 100 for ease of comparison (the original total score possible for the Hoyo rubric is 18 and that for YTC rubric is 24). The t-test, Analysis of Variance (ANOVA) and correlation studies were done (all using $\alpha=0.05$) to study the effect of traditional approaches used to find:

a) What are the differences among the means for (1) instructional approach used, (2) student level (freshmen and senior), and (3) courses in the study?
b) The effect of the time period in the study (first month-early semester; second month-middle of the semester and third month-towards the end of the semester).
c) The correlation between the student scores on critical-thinking based on the Hoyo rubric and the YTC rubric.

Hoyo Rubric

The Hoyo rubric was developed by educational researcher Mariah Oliver- Hoyo at North Carolina State University as a result of the Hewlett Initiative (2003). Hoyo developed a rubric to use with freshmen chemistry students for a course especially designed to improve critical thinking skills. The cognitive traits that define critical thinking skills are incorporated in the rubric. Guided-inquiry based instruction sets the stage for qualitatively promoting critical thinking skills. The rubric was used to evaluate written reports for critical thinking skills of freshmen students in a newly designed chemistry course, CH101. In this study, Hoyo evaluated 18 written reports of students. Students chose their writing assignment topic from a list provided by the instructor. In this study, students had different titles over a range of topics in applied chemistry. Students conducted their investigations and turned in three drafts over three months during the semester. Student written work was graded using Oliver-Hoyo's rubric. The rubric was used in discussion with the students in the course and students evaluated their written work for each draft after receiving feedback from the instructor for the level attained for each of the traits of critical thinking. The purpose of Hoyo's study was to assess the changes in the critical thinking skills of students as an outcome of an inquiry-based course in chemistry.

The Hoyo rubric is based on a primary trait analysis scale (PTA). The PTA scale is a rubric that was developed to explicitly convey to students the expectations for a given classroom assignment and how it corresponds to the course grades. The Hoyo rubric evaluates writing skills based on the characteristics of the abstract, sources of information, relevance, content, and presentation. These characteristics in student writing are related to cognitive skills outlined in Bloom's taxonomy and each trait is scored on a scale of 1 to 3 with 1 being lowest and 3 being the highest score.

The Hoyo rubric was slightly modified to evaluate the traditional and guided-inquiry based SWH laboratory reports. In this study laboratory reports were scored based on the Hoyo rubric for the traditional Chemistry167L laboratory for engineers, guided-inquiry based Chemistry 177L laboratory for science and engineering majors, and Chemistry 401L, the traditional advanced inorganic chemistry laboratory.

Table 9: Modified Hoyo critical thinking evaluation rubric for written reports.

Trait evaluated	Cognitive Skill applied	Level/ Score	Criterion for obtaining levels (scores) of the rubric
Abstract	Synthesis	3	All main points of information are succinctly presented. The title/ purpose, hypothesis/ research question is clearly stated. The purpose is written in a professional way in less than 100 words long and contains a clear articulation of thesis statement or argument.
		2	Some points of information or keywords are missing, but all the criteria are addressed.
		1	One or more criteria are absent.
Sources of Information	Knowledge and Evaluation	3	Sources of information are appropriately cited in the document. A thorough search of the literature was conducted. The nature of sources is judged to be appropriate. Citations are consistently formatted.
		2	An effort on all criteria is shown.
		1	One or more criteria are absent.
Organization	Analysis	3	Clear section headings are used in the document. Material is presented under the appropriate heading. Information is presented in reasonable amounts. There is a logical and coherent flow of information throughout the document.
		2	Either one of the last two criteria not met. Contains clear section headings with relevant material in each section.
		1	Requires major improvements on all criteria.
Relevance	Knowledge and Application	3	Appropriate scientific terminology is used. The writing in the report integrates information from class, lecture, and activities into new material. The student can provide a link between theory and applications.
		2	One criterion is lacking, but efforts on the other two are shown.
		1	One criterion is lacking, but efforts on the other two are shown.
Content	Comprehension	3	The student's writing conveys new information in the student's own words. Concepts are correctly understood. An appropriate depth of content is present. The writing in the report is simple and direct. The student writes in the active voice rather than passive voice.
		2	The material in the report is not well understood but effort is shown towards comprehension.

Table 9: (continued)

Trait evaluated	Cognitive Skill applied	Level/ Score	Criterion for obtaining levels (scores) of the rubric
Content	Comprehension	1	The content is too broad. Focus is not on the scientific aspect of the topic.
Presentation	Evaluation	3	The report is well written in English and has a professional appearance: handwritten/ typed, neat, and easy to read. All previous formative evaluations were addressed. The presentation conforms to the required format.
		2	Efforts on all criteria were made but not fully achieved.
		1	One or more of the criteria are not met.

York Technical College (YTC) Rubric

The YTC rubric was developed by York Technical College as a part of their Quality enhancement Plan (QEP) to Improve Students' Critical Thinking Skills (2004). Improving students' critical thinking skills was identified as the topic with the greatest potential impact toward improving the quality of student learning, while also meeting the needs of employers. Under the QEP, the YTC team developed a number of critical thinking rubrics and activities to foster critical thinking. In this study the YTC rubric was modified to evaluate the critical thinking skills from student written work.

Table 10: Modified YTC critical thinking rubric for evaluating written reports.

	Advanced-4	Competent-3	Developing-2	Elementary-1
Identify	Clearly identifies the root problem, situation or a question; exhibits an open mind; thinks about own thinking process.	Identifies the problem, situation or a question; exhibits somewhat of an open mind, somewhat clear in stating the problem/ purpose.	Identifies irrelevant ideas as a problem, situation or a question; unable to clearly state the problem in correct words; less open-minded in identifying key issues.	Fails to identify a problem, state a question or a situation; ignores information and exhibits a closed mind.
Gather	Gathers all pertinent information related to the activity; considers all perspectives and assumptions; reflects on the problem or the question.	Gathers some pertinent information related to the activity. Considers most perspectives and assumptions.	Gathers inadequate information; considers only a few perspectives and assumptions.	Gathers no pertinent information; Considers few to non perspectives and assumptions.

Table 10: (continued)

	Advanced-4	Competent-3	Developing-2	Elementary-1
Examine	Identifies relationships between the variables; analyzes information provided by data, observations, and graphs; reflects on the problem or question.	Identifies some key relationships between variables; discovers most relevant elements from information gathered.	Wanders from the question or problem; recognizes some relationships; sorts some relevant elements from gathered information.	Totally ignores the problem or question; does not identify relationships among variables or any trends from data, observations, graphs.
Formulate	Suggests multiple solutions; identifies a position; devises a logical plan of action or procedure; reflects on prior experience to support claims.	Suggests some possible solutions; states an acceptable plan of action or procedure; uses some prior information to support the claims.	Presents very few options and fails to make any claim or take a position; states a marginal procedure; displays lack of connection between prior experiences to support the claims.	Presents no options or solutions; fails to reach a position; does not integrate past experiences to support claim; fails to present an acceptable procedure/ solution.
Apply	Implements the procedure and follows it to conclusion; clearly demonstrates understanding of concepts; produces high quality data and thorough observations.	Implements only parts of the procedure or plan; shows some follow up on ideas; the data and observations are acceptable.	Implements very small part of procedure with little or no follow up; the data and observations are marginal and display lack of rigor.	Does not implement the procedure; fails to reach a conclusion; no data or observations; no illustration of concept in any form.
Evaluate	Notes initial thoughts; judges findings objectively; assesses conclusions in terms of validity or reliability of data and observations; offers alternative solutions (what can work; what can be done); reflects on own thinking process and seeks opportunities for improvement.	Shows some initial thoughts here and there in a report; addresses validity and reliability but does not provide any alternatives; justifies most findings; occasionally reflects on problem or process.	Questions some part of data; skewed reasoning; faulty conclusions; inaccurately interprets information; justifies only a little portion of findings; shows very little reflection on problem or process.	Fails to question data; fails to assess conclusion; incorrect justification of results; no reflection on problem or process.

Results and Discussion

Distribution(s) for groups in the study:

The bar graphs (Fig 1a-1d) below indicate the groups in the study and different levels in a given group. There are three courses in study and two different instructional approaches are used namely traditional and inquiry-based Science Writing Heuristic approach. Number of students from each group=10 and the number of reports selected from each group=30 (3 reports per student). Table 11 provides a summary of the distributions for the groups in study.

Figure 1: Groups in the study and different levels in a given group.

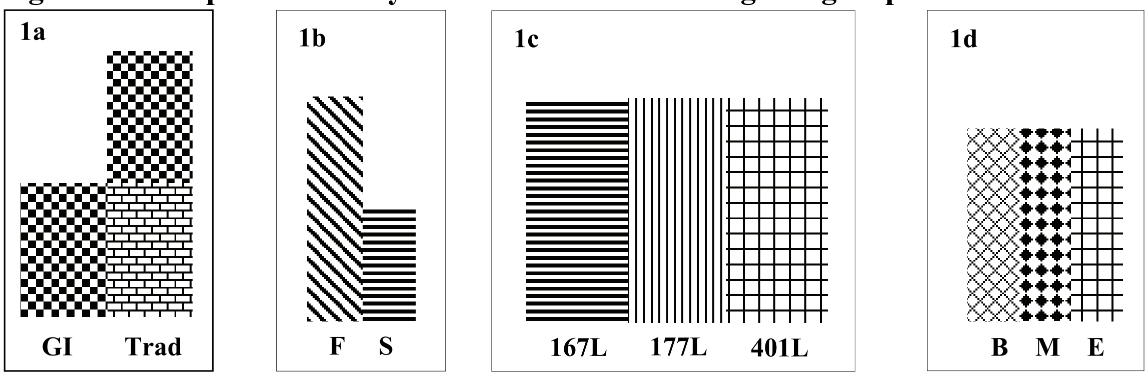


Figure (1a): Instructional approach, guided-inquiry (GI); traditional (Trad). Figure (1b): Student levels, Freshman (F); Senior (S). Figure (1c): Chemistry laboratory courses. Figure (1d): Time intervals of semester, beginning (B); middle (M); end (E).

Table 11: Distributions of groups and laboratory reports per group.

Student level (Fig. 1b)	Freshmen (F) (N=60)		Seniors (S) (N=30)
Course in study (Fig. 1c)	177 L (N=30)	167L (N=30)	177 L (N=30)
Instruction (Fig. 1a)	GI (N=30)	Traditional (N=60)	
Time in Semester (Fig. 1d)	Early (B) (N=30)	Middle (M) (N=30)	End (E) (N=30)

Baseline comparison for 177L, 167L, 401L for scores on first laboratory activity

The mean scores and standard deviations were compared for first laboratory reports. The students receiving guided-inquiry based instructions have a higher mean score for laboratory reports as compared to students instructed using traditional instruction. It was found that scores for the laboratory reports for students in the three courses and two treatment groups are equivalent (Table 12). Analysis of variance showed no differences between the mean scores $F(2, 27)=0.368$, $p=0.6955$.

Table 12: Means and standard deviations for first set of laboratory reports.

Course	N	Mean	Standard Deviation
177L	10	62.06	12.11
167L	10	56.56	7.99
401 L	10	60.00	20.48

Table 13: One-way ANOVA table for laboratory report scores in the beginning of semester.

Source	DF	Sum of Squares	Mean Square	F-ratio	Prob>F
(177L, 167L, 401L)	2	154.633	77.137	0.3680	<0.6955
Error	27	5672.737	210.10		
C. Total	29	5827.371			

Distribution(s) of Traits based on YTC rubric

The YTC rubric explores six traits on critical thinking and each trait is scored on a scale of 1 to 4. Each score indicates the stage of critical thinking. A score of 1 indicates an elementary level of critical thinking; 2 is a developed stage of critical thinking; 3 is a competent stage; and a score of 4 implies an advanced level of critical thinking on a given trait. Distributions were plotted for each course in the study for the scores obtained according to the YTC rubric with regard to each trait and for each time period in the semester for a given course.

Based on distribution by course, Chemistry 177L students receiving guided-inquiry based instruction have a statistically significant score on various traits of critical thinking as compared to Chemistry 167L students receiving traditional instruction (Table 14, and 15) In Chemistry 177L, only two reports out of ten analyzed indicate an advanced level for application and evaluation in the beginning of the semester. In the middle of the semester two out of ten reports analyzed show advanced critical thinking (CT) score on the traits of identification of the problems and evaluation of the information, data and observations.

Towards the end of semester three out of ten reports displayed an advanced level on the traits of application and evaluation (Table 16). The trend for Chemistry 167L and Chemistry 401L reports indicates fewer scores for an advanced level on traits of critical thinking. It can further be seen that the YTC distribution of scores indicates that students receiving traditional instruction show very little improvement on various traits during the course of the semester (Table 17).

Table 14: Distribution, mean score and standard deviations for traits based on YTC rubric for laboratory reports during the first month of semester for Chemistry 177L, 167L, and 401L.

Trait	Identify				Gather				Examine				Formulate				Apply				Evaluate			
Score possible	4	3	2	1	4	3	2	1	4	3	2	1	4	3	2	1	4	3	2	1	4	3	2	1
177L Score Frequency	-	-	8	2	1	4	5	-	-	5	5	-	-	2	8	-	1	1	7	1	1	2	6	1
Mean Score	1.8				2.6				2.5				2.2				2.2				2.3			
S.D.	0.421				0.699				0.527				0.421				0.788				0.823			
167L Score Frequency	1	-	4	5	-	1	6	3	-	1	5	4	-	1	4	5	-	1	2	7	-	-	2	8
Mean Score	1.7				1.8				1.7				1.6				1.4				1.2			
S.D.	0.948				0.632				0.674				0.699				0.699				0.421			
401L Score Frequency	1	2	4	3	-	2	3	5	-	1	3	6	-	2	3	5	-	2	2	6	-	2	1	7
Mean Score	2.1				1.7				1.5				1.7				1.6				1.5			
S.D.	0.994				0.823				0.707				0.823				0.843				0.849			

Table 15: Distribution, mean score and standard deviations for traits based on YTC rubric for laboratory reports during the second month of the semester for Chemistry 177L, 167L, and 401L.

Trait	Identify				Gather				Examine				Formulate				Apply				Evaluate			
Score possible	4	3	2	1	4	3	2	1	4	3	2	1	4	3	2	1	4	3	2	1	4	3	2	1
177L Score Frequency	1	3	5	1	-	4	6	-	1	4	5	-	-	8	2	-	4	3	3	-	3	5	2	-
Mean Score	2.4				2.4				2.6				2.8				3.1				3.1			
S.D.	0.843				0.516				0.699				0.421				0.875				0.737			
167L Score Frequency	-	4	3	3	1	1	3	5	1	-	4	5	-	1	2	7	1	-	3	6	1	-	3	6
Mean Score	2.1				1.8				1.7				1.4				1.6				1.6			
S.D.	0.875				1.03				0.948				0.699				0.966				0.966			
401L Score Frequency	-	4	4	2	-	-	5	5	1	1	1	7	-	1	2	7	-	2	-	8	1	1	-	8
Mean Score	2.2				1.5				1.6				1.4				1.4				1.5			
S.D.	0.788				0.527				1.074				0.699				0.843				1.081			

Table 16: Distribution, mean score and standard deviations for traits based on YTC rubric for laboratory reports during the third month of semester for Chemistry 177L, 167L, and 401L.

Trait	Identify				Gather				Examine				Formulate				Apply				Evaluate			
Score possible	4	3	2	1	4	3	2	1	4	3	2	1	4	3	2	1	4	3	2	1	4	3	2	1
177L Score Frequency	-	4	3	3	-	7	2	1	-	5	3	2	-	6	2	2	2	4	3	1	1	6	1	2
Mean Score	2.1				2.6				2.3				2.4				2.7				2.6			
S.D.	0.875				0.669				0.823				0.843				0.948				0.966			
167L Score Frequency	-	3	2	5	-	1	7	2	-	2	7	1	-	2	5	3	-	1	7	2	-	2	2	6
Mean Score	1.8				1.9				2.1				1.9				1.9				1.6			
S.D.	0.918				0.567				0.567				0.737				0.567				0.843			
401L Score Frequency	-	1	5	4	1	-	4	5	1	3	1	5	-	3	2	5	-	-	4	6	-	-	7	3
Mean Score	1.7				1.7				2				1.8				1.4				1.7			
S.D.	0.674				0.948				1.154				0.918				0.516				0.483			

Table 17: Average scores for YTC rubric for Chemistry 177L, 167L, and 401L.

YTC Mean Score	177L	167L	401L
YTC Score Early in Semester (out of 24) Mean (SD)	13.6 (2.50)	9.4 (2.91)	10.1 (4.17)
YTC Score Early in Semester (Scaled to 100) Mean (SD)	47.49(10.43)	39.16 (12.13)	42.08 (17.39)
YTC Score Middle of Semester (out of 24) Mean (SD)	16.4 (2.41)	10.2 (4.18)	9.6 (4.19)
YTC Score Middle of Semester (Scaled to 100) Mean (SD)	64.16 (10.05)	42.49 (17.43)	39.99 (17.48)
YTC Score End of Semester (out of 24) Mean (SD)	14.7 (4.42)	11.2 (3.35)	10.2 (2.74)
YTC Score End of Semester (Scaled to 100) Mean (SD)	71.66 (8.97)	46.66 (13.33)	41.24 (12.49)

The average scores for the YTC rubric (Table 17) indicates that students in Chemistry 177L show an increase in laboratory report score during the course of semester with mean scores of 47.49 (S.D.=10.43) at the beginning of the semester; 64.16 (S.D=10.05) in the middle of the semester; and 71.66 (S.D.=8.97) towards the end of the semester. Student report scores for Chemistry 167L, though, start at a lower mean score of 39.16 (S.D.=12.13) at the beginning of semester; there is an improvement in mean scores towards the middle (M=42.49; S.D.=17.43) and end of semester (M=46.66; S.D.=13.33).

Test(s) of significance:

In order to examine the differences between the groups statistical tests of significance were performed. A t-test was used to for the comparison of the means of two groups. A t-test helps in establishing the difference between mean scores of two groups relative to the variability in scores. In simple words, it is a ratio of the “spread” which is the difference in means between the two groups and the “noise” which is the variability between the groups in study. The simplest form of ANOVA called one-way ANOVA is used to compare two or more means. The one-way ANOVA is used to compare relations between a measurement variable *y* and a categorical variable *x* that has two or more categories. In the case where *x* has just two categories ANOVA yields similar output as the two-sample t-test. In addition to testing hypothesis for two means, the ANOVA method calculates ratios of variances which are obtained from between and within group sum of squares. This ratio follows an F-distribution. An F- distribution or Fisher’s distribution is continuous and is depends on the numerator and denominator degrees of freedom. ANOVA tests serve to determine the differences in variances; simultaneously compare several means as well as explain the proportion of variance by regression (Hamilton, 1995).

A one-way ANOVA was used to compare critical thinking score averages on reports that were obtained from students:

a) With guided-inquiry based instruction versus students instructed using a traditional approach (Table 18).
b) In the freshmen courses versus in the advanced chemistry course (Table 19).
c) Enrolled in different laboratory courses (Table 20).
d) For different times of the semester from which the reports were drawn (Table 21).

An independent samples t-test (Table 18) indicated the YTC critical thinking score means were statistically significantly higher for students who received guided-inquiry based instruction (M=14.7, S.D. 3.36; as compared to student reports for traditionally instructed students (M=10.07, S.D. 3.57; t(61.42)=5.99, p<.0001, d=1.32). Similarly, a t-test comparison for the means of students based on freshmen and advanced level of chemistry (Table 19) indicates statistically significantly higher means for students at freshmen level general chemistry (M=12.47, S.D.=4.05) when compared to students in advanced level inorganic chemistry laboratory (M=9.86, SD=3.70; t(63.04)=3.04, p=.0034, d=0.66).

An ANOVA test was performed on the average YTC critical thinking scores for students in 177L, 167L and 401L (Table 20). The results of the one-way ANOVA indicate a statistically significant effect of course of study on YTC critical thinking scores F(2, 87)=17.2, p=<.0001. However, when looking at the effect of time, i.e., the time of the semester from which the reports were drawn (the first month, second month, and third month), there is no statistical significant effect of time on YTC critical thinking score F(2, 87)=2.81; p=.063 (Table 21).

Table 18: Two-tailed t-test for CT score averages on YTC rubric by treatment.

Guided Inquiry (N=30)		Traditional (N=60)						
Mean	SD	Mean	SD	t-ratio	Prob>|t|	DF	Cohen's d	Effect Size r
14.66	3.356	10.067	3.569	-5.99	0.0001*	61.42	1.32	0.553

Table 19: Two-tailed t-test for CT score averages on YTC rubric by level of students.

Freshmen		Senior		Statistical Analysis				
Mean	SD	Mean	SD	t-ratio	Prob>|t|	DF	Cohen's d	Effect Size r
12.466	4.05	9.86	3.70	-3.041	0.0034*	63.04	0.669	0.317

Table 20: One-way analysis for CT score averages on YTC rubric by courses.

Source	DF	Sum of Squares	Mean Square	F-ratio	Prob>F
(177L, 167L, 401L)	2	425.60	212.80	17.205	<0.0001[a]
Error	87	1076.0	12.368		
C. Total	89	1501.6			

Table 21: One-way analysis for CT scores on averages on YTC rubric by time.

Source	DF	Sum of Squares	Mean Square	F-ratio	Prob>F
Time Code [b]	2	92.06	46.033	2.8143	<0.0638
Error	87	1409.53	16.201		
C. Total	89	1501.6			

[a] Significant at $\alpha = 0.05$.

[b] Note time code indicates different times in the semester (first month, second month, and third month).

Distribution(s) of scores based on Hoyo Rubric

Student laboratory reports were scored using the Hoyo rubric for six different traits of critical thinking that also relate to the cognitive skills that are applied while writing laboratory reports on chemistry activities. According to the Hoyo rubric the maximum score possible on a given trait is 3 and the minimum score possible is 1. The distributions obtained for traits of critical thinking for student laboratory reports are summarized in Table 22-Table 25. As can be seen, the student written reports have no clear pattern during the first month of the semester for Chem 177L, 167L, and 401L (Table 22). The students in Chem 177L have a higher mean on the traits of content (M=1.8, S.D.=0.63) and presentation (M=1.8, S.D.=0.78). The students in 401L have a higher mean on the traits abstract (M=1.6, S.D 0.69) and sources of information (M=1.6; S.D. =0.69). For the laboratory reports drawn from the second month of the semester (Table 23), there is a shift in the distribution for scores on traits and the mean for each trait. The laboratory reports of students in 177 show an increase in mean for the traits abstract (M=1.7; S.D.=0.48) and sources of information (M=2.2, S.D.=0.42) and further increase in the mean scores on traits of organization, relevance, content, presentation (Table 23). Reports of Chem167 students show an improvement in the mean scores during the second month as compared to the first month on the six traits of Hoyo rubric. The Chem401 reports show a decline on traits of content (M=1.2, S.D.=0.63) and presentation (M=1.3, S.D.=0.67). During the third month, the reports of Chem177 students show a slight decrease on mean score for traits of sources of information (M=2.0, S.D.=0.66) and presentation (M=1.9, S.D.=0.73) and very slight improvement on relevance (M=2.3, S.D. 0.67). Student reports for Chem167 show improvement in distributions for trait of relevance (M=1.6, S.D. =0.69) and content (M=1.4, S.D. =0.69). The Chem401 reports show a decline in score for abstract (M=1.1, S.D.=0.31) as compared to the second month in the semester (Table 24).

Table 22: Distribution, mean scores and standard deviations for traits based on Hoyo rubric for laboratory reports during the first month of the semester for Chem 177L, 167L and 401L.

Trait evaluated/ Cognitive Skill Applied	Abstract/ Synthesis			Sources of information/ Knowledge and Evaluation			Organization /Analysis			Relevance/ Knowledge and application			Content/ Comprehension			Presentation/ Evaluation		
Score possible	3	2	1	3	2	1	3	2	1	3	2	1	3	2	1	3	2	1
177L Score Frequency	3	-	7	-	5	5	-	6	4	-	5	5	1	6	3	2	4	4
Mean Score		1.3			1.5			1.6			1.5			1.8			1.8	
S.D.		0.483			0.527			0.516			0.527			0.632			0.788	
167L Score Frequency	-	4	6	1	1	8	-	3	7	1	1	8	-	-	10	-	1	9
Mean Score		1.4			1.3			1.3			1.3			1			1.1	
S.D.		0.516			0.674			0.483			0.674			-			0.316	
401L Score Frequency	1	4	5	1	4	5	-	4	6	1	1	8	1	2	7	1	2	7
Mean Score		1.6			1.6			1.4			1.3			1.4			1.4	
S.D.		0.699			0.699			0.516			0.674			0.699			0.699	

Table 23: Distributions, mean scores and standard deviations for traits based on Hoyo rubric for laboratory reports during the second month of the semester for Chem 177L, 167L and 401L.

Trait evaluated/ Cognitive Skill Applied	Abstract/ Synthesis			Sources of information/ Knowledge and Evaluation			Organization /Analysis			Relevance/ Knowledge and application			Content/ Comprehension			Presentation/ Evaluation		
Score possible	3	2	1	3	2	1	3	2	1	3	2	1	3	2	1	3	2	1
177L Score Frequency	-	7	3	2	8	-	4	5	1	3	6	1	4	5	1	4	3	3
Mean Score		1.7			2.2			2.3			2.2			2.3			2.1	
S.D.		0.483			0.421			0.674			0.632			0.674			0.875	
167L Score Frequency	-	6	4	-	3	7	2	1	7	-	2	8	1	-	9	1	1	8
Mean Score		1.6			1.3			1.5			1.2			1.2			1.3	
S.D.		0.516			0.483			0.849			0.421			0.632			0.674	
401L Score Frequency	3	2	5	-	4	6	1	2	7	-	2	8	1	1	8	1	-	9
Mean Score		1.8			1.4			1.4			1.4			1.3			1.2	
S.D.		0.918			0.516			0.699			0.843			0.674			0.632	

Table 24: Distributions, mean scores and standard deviations for traits based on Hoyo rubric for laboratory reports during the third month of the semester for Chem 177L, 167L and 401L.

Trait evaluated/ Cognitive Skill Applied	Abstract/ Synthesis			Sources of information/ Knowledge and Evaluation			Organization /Analysis			Relevance/ Knowledge and application			Content/ Comprehension			Presentation/ Evaluation		
Score possible	3	2	1	3	2	1	3	2	1	3	2	1	3	2	1	3	2	1
177LScore Frequency	1	8	1	2	6	2	3	7	-	4	5	1	6	3	2	2	5	3
Mean Score		2			2			2.3			2.3			2.3			1.9	
S.D.		0.471			0.667			0.483			0.674			0.823			0.737	
167L Score Frequency	-	4	6	1	2	7	-	3	7	1	4	5	1	2	7	-	2	8
Mean Score		1.4			1.4			1.3			1.6			1.4			1.2	
S.D.		0.516			0.699			0.483			0.699			0.699			0.421	
401L Score Frequency	-	1	9	-	3	7	1	2	7	2	2	6	-	2	8	-	1	9
Mean Score		1.1			1.3			1.4			1.6			1.2			1.2	
S.D.		0.316			0.483			0.699			0.843			0.421			0.632	

The overall average scores on traits of critical thinking for three different time periods during the semester for the Hoyo rubric and the scaled scores are summarized in Table 25 to provide a quick snapshot of the mean and standard deviations for overall critical thinking scores based on the Hoyo rubric.

Table 25: Average scores for reports based on Hoyo rubric for Chem 177L, 167L and 401L.

Hoyo Mean Score	177L	167L	401L
Score Early in Semester (out of 18) Mean (SD)	9 (2.357)	7.4(1.77)	8.1 (2.46)
Score Early in Semester (Scaled to 100) Mean (SD)	49.99 (13.09)	41.10(9.86)	44.99(13.7)
Score Middle of Semester (out of 18) Mean (SD)	12.1(2.99)	8.1(2.68)	7.8(3.04)
Score Middle of Semester (Scaled to 100) Mean (SD)	67.22(16.65)	44.99(14.91)	43.33(16.93)
Score End of Semester (out of 18) Mean (SD)	12.4 (1.95)	8.1(2.55)	7.5 (2.06)
Score End of Semester (Scaled to 100) Mean (SD)	68.88(10.86)	44.99(14.21)	41.66(11.49)

Test(s) of significance

The laboratory reports means for traits based on Hoyo rubric were tested for significance. A t-test for instructional approach used (Table 26) indicated a statistical significant difference for the reports of students who received guided-inquiry based instruction (M=11.1; S.D. 2.8) as compared to reports from courses that were based on traditional laboratory instruction (M=7.8, S.D. 2.3, t(49.7)=5.51, p=<.0001, d=1.26). The comparison of student report mean scores using an independent samples t-test based on the levels of students (Table 27) shows student critical thinking scores to be statistically significantly different for students in freshmen general chemistry (M=9.51; S.D.=3.06) versus students in advanced chemistry laboratory (M=7.8; S.D.=2.48, t(70.0)=2.85; p=.005, d=0.61).

Table 26: Comparison of CT score averages on the Hoyo rubric by treatment.

Guided Inquiry		Traditional		Statistical Analysis				
Mean	SD	Mean	SD	t-ratio	Prob>|t|	DF	Cohen's d	Effect Size r
11.167	2.853	7.833	2.380	-5.510	<.0001*	49.730	1.26	0.535

Table 27: Comparison of CT score averages on the Hoyo rubric by level of students.

Freshmen		Senior		Statistical Analysis				
Mean	SD	Mean	SD	t-ratio	Prob>|t|	DF	Cohen's d	Effect Size r
9.516	3.06	7.80	2.48	-2.85	0.0057*	70.07	0.615	0.294

A one-way analysis of variance of the Hoyo critical thinking score means of students in the three courses shows the effect of courses on the mean scores to be statistically significant $F(2,89)=16.95$, $p=<.0001$ (Table 28). A one-way analysis was done of Hoyo rubric score means for the time in semester during which the laboratory reports were drawn for students in three groups. The one-way ANOVA indicated no significant effect of time on critical thinking mean $F(2,87)=1.54, p=.021$ (Table 29).

Table 28: One-way analysis for CT score averages on the Hoyo rubric by courses.

Source	DF	Sum of Squares	Mean Square	F-ratio	Prob>F
(177L, 167L, 401L)	2	222.88	114.44	16.951	<0.0001[a]
Error	87	570.43	6.557		
C. Total	89	792.72			

[a] Significant at $\alpha = 0.05$.

Table 29: One-way analysis for CT score averages on the Hoyo rubric by time.

Source	DF	Sum of Squares	Mean Square	F-ratio	Prob>F
Time Code [b]	2	27.22	13.611	1.5469	<0.2187
Error	87	765.50	8.798		
C. Total	89	792.72			

[b] Note time code indicates different times in the semester (first month; second month and third month).

Correlations:

To understand the relationship between the YTC and Hoyo rubrics on critical thinking skills from student laboratory reports, a correlation analysis was performed using the JMP 9.0 statistical package. Correlations are used to quantify the relationship between two numerical variables using a correlation coefficient. Two measures of critical thinking skills were used, namely the YTC rubric and the Hoyo rubric for analyzing laboratory reports of same groups of students on 6 traits of critical thinking for each rubric. The goal was to understand the correlation between the scores on critical thinking on one rubric with the scores on critical thinking with the other rubric. The null hypothesis was that there is no relationship between the average critical thinking scores on the Hoyo rubric and the YTC rubric between the a) treatment and control groups, b) different courses under study, c) freshmen and senior chemistry students, and d) time of the semester from which the reports were drawn (or H_0:r=0). The alternative hypothesis is that the correlation between the groups is not equal to zero (H_A:r≠0).

Correlation studies were performed average critical thinking scores on both the YTC and Hoyo rubrics. Correlation between the two rubrics was studied for:

a) Courses during the times of semester when the reports were drawn;
b) Each course separately;
c) Freshmen students and advanced chemistry student reports;
d) The time of the semester during which the reports were drawn separately;
e) Guided-inquiry based instruction;
f) Traditional laboratory instruction.

Based on the correlation tables for each of the factors mentioned above (a-f), the correlations are summarized via Table 30–Table 48. It was found that the YTC mean score on critical thinking and Hoyo mean scores were positively correlated. A quick summary for each table follows along with the statistically significant correlation coefficient.

a) For Chem177L reports in the first month of the semester, Pearson's r(10)=.92, p<.0001 (Table 30).

b) For Chem177L reports in the second month of the semester, Pearson's $r\ (10)=.90$, $p<.0004$ (Table 31).

c) For Chem177L reports in the third month of the semester Pearson's $r(10)=0.90$, $p<.0003$ (Table 32).

d) For Chem167L reports in the first month of the semester Pearson's $r(10)=0.88$, $p<.0006$ (Table 33).

e) For Chem167L reports in the second month of the semester Pearson's $r(10)=0.94$, $p<.0001$ (Table 34).

f) For Chem167L reports in the third month of the semester Pearson's $r(10)=0.88$, $p<.0006$ (Table 35).

g) For Chem401L reports in the first month of the semester Pearson's $r(10)=0.97.p<.0001$ (Table 36).

h) For Chem401L reports in the second month of the semester Pearson's $r(10)=0.99$, $p<.0001$ (Table 37).

i) For Chem401L reports in the third month of the semester Pearson's $r(10)=0.94,p<.0001$ (Table 38).

j) For the average score on all reports for Chem177L Pearson's $r(30)=0.90,p<.0001$ (Table 39).

k) For the average score on all reports for Chem167L Pearson's $r(30)=0.90,p<.0001$ (Table 40).

l) For the average score on all reports for Chem401L Pearson's $r(30)=0.96,p<.0001$ (Table 41).

m) For all *freshmen* chemistry students' reports, mean CT scores Pearson's $r(60)=0.92, p=.0001$ (Table 42).

n) For all *advanced* chemistry students' reports, mean CT scores Pearson's $r(30)=0.96, p<.0001$ (Table 43).

o) For reports in the first month of the semester, Pearson's $r(30)=0.92$, $p<.0001$ (Table 44).

p) For reports in the second month of semester, Pearson's $r(30)=0.94$, $p<.001$ (Table 45).

q) For reports in third month of semester Pearson's $r(30)=0.95, p<.0001$ (Table 46).

r) For reports for students receiving guided-inquiry based instruction Pearson's $r(30)=0.90$, $p<.0001$ (Table 47).

s) For reports of students receiving traditional laboratory instruction Pearson's $r(60)=0.93$, $p<.0001$ (Table 48).

Table 30: Correlation between the average scores using the Hoyo and YTC rubrics for 177L, early in semester.

177L (Guided Inquiry) Early in Semester		YTC score	Hoyo score
	Pearson Correlation	1.000	0.922
YTC score	Sig. (2-tailed)		.0001[a]
	N	10	10
	Pearson Correlation	0.922	1.000
Hoyo score	Sig. (2-tailed)		.0001[a]
	N	10	10

[a] Correlation is statistically significant at the 0.05 level (2-tailed).

Table 31: Correlation between the average scores on the Hoyo and YTC rubrics for Chem177L, middle of semester.

177L (Guided Inquiry) Middle of Semester		YTC score	Hoyo score
	Pearson Correlation	1.000	0.900
YTC score	Sig. (2-tailed)		.0004[a]
	N	10	10
	Pearson Correlation	0.900	1.000
Hoyo score	Sig. (2-tailed)		.0004[a]
	N	10	10

Table 32: Correlation between the average scores on the Hoyo and YTC rubrics for Chem177L, end of the semester.

177L (Guided Inquiry) End of Semester		YTC score	Hoyo score
YTC score	Pearson Correlation	1.000	0.904
	Sig. (2-tailed)		.0003[a]
	N	10	10
Hoyo score	Pearson Correlation	0.904	1.000
	Sig. (2-tailed)		.0003[a]
	N	10	10

Table 33: Correlation between the average scores on the Hoyo and YTC rubrics for Chem167L, early in semester.

167L (Traditional) Early in Semester		YTC score	Hoyo score
YTC score	Pearson Correlation	1.000	0.888
	Sig. (2-tailed)		.0006 [a]
	N	10	10
Hoyo score	Pearson Correlation	0.888	1.000
	Sig. (2-tailed)		.0006 [a]
	N	10	10

Table 34: Correlation between the average scores on the Hoyo and YTC rubrics for Chem167L, middle of semester.

167L (Traditional) Middle of Semester		YTC score	Hoyo score
YTC score	Pearson Correlation	1.000	0.947
	Sig. (2-tailed)		.0001[a]
	N	10	10
Hoyo score	Pearson Correlation	0.947	1.000
	Sig. (2-tailed)		.0001[a]
	N	10	10

Table 35: Correlation between the average scores on the Hoyo and YTC rubrics for Chem167L, end of semester.

167L (Traditional) End of Semester		YTC score	Hoyo score
YTC score	Pearson Correlation	1.000	0.889
	Sig. (2-tailed)		.0006 [a]
	N	10	10
Hoyo score	Pearson Correlation	0.889	1.000
	Sig. (2-tailed)		.0006 [a]
	N	10	10

Table 36: Correlation between the average scores on the Hoyo and YTC rubrics for Chem401L, early in semester.

401L (Traditional) Early in Semester		YTC score	Hoyo score
	Pearson Correlation	1.000	0.979
YTC score	Sig. (2-tailed)		.0001[a]
	N	10	10
	Pearson Correlation	0.979	1.000
Hoyo score	Sig. (2-tailed)		.0001[a]
	N	10	10

Table 37: Correlation between the average scores on the Hoyo and YTC rubrics for Chem401L, middle of semester.

401L (Traditional) Middle of Semester		YTC score	Hoyo score
	Pearson Correlation	1.000	0.992
YTC score	Sig. (2-tailed)		.0001[a]
	N	10	10
	Pearson Correlation	0.992	1.000
Hoyo score	Sig. (2-tailed)		.0001[a]
	N	10	10

Table 38: Correlation between the average scores on the Hoyo and YTC rubrics for Chem401L, end of semester.

401L (Traditional) End of Semester		YTC score	Hoyo score
	Pearson Correlation	1.000	0.940
YTC score	Sig. (2-tailed)		.0001[a]
	N	10	10
	Pearson Correlation	0.940	1.000
Hoyo score	Sig. (2-tailed)		.0001[a]
	N	10	10

Table 39: Correlation between Hoyo and YTC rubrics on average scores on laboratory reports for Chem167L.

167L Average Score on Reports		YTC score	Hoyo score
	Pearson Correlation	1.000	0.906
YTC score	Sig. (2-tailed)		.0001[a]
	N	30	30
	Pearson Correlation	0.906	1.000
Hoyo score	Sig. (2-tailed)		.0001[a]
	N	30	30

Table 40: Correlation between Hoyo and YTC rubrics for average scores on laboratory reports for Chem177L.

177L Average Score on Reports		YTC score	Hoyo score
YTC score	Pearson Correlation	1.000	0.902
	Sig. (2-tailed)		.0001[a]
	N	30	30
Hoyo score	Pearson Correlation	0.902	1.000
	Sig. (2-tailed)		.0001[a]
	N	30	30

Table 41: Correlation between Hoyo and YTC rubrics for average scores on laboratory reports for Chem401L.

401L Average Score on Reports		YTC score	Hoyo score
YTC score	Pearson Correlation	1.000	0.968
	Sig. (2-tailed)		.0001[a]
	N	30	30
Hoyo score	Pearson Correlation	0.968	1.000
	Sig. (2-tailed)		.0001[a]
	N	30	30

Table 42: Correlation between Hoyo and YTC rubrics for average scores for *freshmen* chemistry student reports.

Average Score for Freshmen Chemistry Student Reports		YTC score	Hoyo score
YTC score	Pearson Correlation	1.000	0.928
	Sig. (2-tailed)		.0001[a]
	N	60	30
Hoyo score	Pearson Correlation	0.928	1.000
	Sig. (2-tailed)		.0001[a]
	N	60	60

Table 43: Correlation between Hoyo and YTC rubrics for average scores for *advanced* chemistry student reports.

Average Score for Advanced Chemistry Student Reports		YTC score	Hoyo score
YTC score	Pearson Correlation	1.000	0.968
	Sig. (2-tailed)		.0001[a]
	N	30	30
Hoyo score	Pearson Correlation	0.968	1.000
	Sig. (2-tailed)		.0001[a]
	N	30	30

Table 44: Correlation between Hoyo and YTC rubrics for average scores by time of semester (average of reports from first month).

Score by Time (Average of Reports from First Month)		YTC score	Hoyo score
YTC score	Pearson Correlation	1.000	0.927
	Sig. (2-tailed)		.0001[a]
	N	30	30
Hoyo score	Pearson Correlation	0.927	1.000
	Sig. (2-tailed)		.0001[a]
	N	30	30

Table 45: Correlation between Hoyo and YTC rubrics for average scores by time of semester (average of reports from second month).

Score by Time (Average of Reports from Second Month)		YTC score	Hoyo score
YTC score	Pearson Correlation	1.000	0.949
	Sig. (2-tailed)		.0001[a]
	N	30	30
Hoyo score	Pearson Correlation	0.949	1.000
	Sig. (2-tailed)		.0001[a]
	N	30	30

Table 46: Correlation between Hoyo and YTC rubrics for average scores by time of semester (average of reports from third month).

Score by Time (Average of Reports from Third Month)		YTC score	Hoyo score
YTC score	Pearson Correlation	1.000	0.954
	Sig. (2-tailed)		.0001[a]
	N	30	30
Hoyo score	Pearson Correlation	0.954	1.000
	Sig. (2-tailed)		.0001[a]
	N	30	30

Table 47: Correlation between Hoyo and YTC rubrics for averages scores for students receiving guided-inquiry based instruction.

Rubric for Averages of Guided-Inquiry Based Instruction		YTC score	Hoyo score
YTC score	Pearson Correlation	1.000	0.902
	Sig. (2-tailed)		.0001[a]
	N	30	30
Hoyo score	Pearson Correlation	0.902	1.000
	Sig. (2-tailed)		.0001[a]
	N	30	30

Table 48: Correlation between Hoyo and YTC rubrics for average scores for students receiving traditional laboratory instruction.

Rubric for Averages of Traditional Laboratory Instruction		YTC score	Hoyo score
	Pearson Correlation	1.000	0.938
YTC score	Sig. (2-tailed)		.0001[a]
	N	60	60
	Pearson Correlation	0.938	1.000
Hoyo score	Sig. (2-tailed)		.0001[a]
	N	60	60

Two-way ANOVA tests

In order to assess the factors that factors influenced the mean critical thinking scores on the YTC rubric and the Oliver-Hoyo rubric for the laboratory reports of students in the three different courses for which two different instructional approaches were used, a two-way analysis of variance was performed. A two-way ANOVA refers to an analysis of variance with a measurement variable (y) and two categorical variables x_1 and x_2. A two-way ANOVA thus allows for many different F-statistic tests such as those listed below (Hamilton, 1995):

1. A test for the overall model: rejecting or keeping the null hypothesis that a population mean of y is same at every level of x_1 and x_2.
2. Test for the main effect of variable x_1: rejecting the null hypothesis such that keeping x_2 constant, the population mean of variable y is found to be same for each value of x_1. Likewise testing for the main effect of variable x_2 such that when keeping x_1 constant the population mean of variable y is found to be same for each x_2.
3. Test for the interaction effects of the different levels of x: rejecting the null hypothesis that the cell- to -cell variances in the population means of variable y indicate some interaction of the variable x and y and not just the sum of the x_1 and x_2 main effects.

Effect of Time and course on YTC score

Table 49 shows the ANOVA table and Table 50 shows the interaction effects of time and course on the YTC score for student reports. As evident from the effect tests the course variable has a statistical significant effect on YTC mean scores $F(2)=19.53$, $p=.0001$ and the time of semester from which the reports were drawn also impacts YTC scores significantly $F(2)=4.22$, $p=.017$, however the effect of time of semester is less significant at $\alpha=.05$. The relation between course and time was initially found to be not significantly different for YTC mean scores on critical thinking $F(4)=2.33$, $p=.06$ and there appeared to be no interaction between course and time. On slicing the courses and time and on setting the contrasts it was found that the slice for Chem177L had a significant effect with $F(2,81)=8.09$, $P=.0006$; the slice time code B (reports from the middle of the semester was significant with $F(2,81)=9.34$, $p=.0002$; and the slice time code C (reports from the end of the semester) was significant $F(2,81)=13.92$, $p=.0001$ (Table 50, Fig 2)

Table 49: Analysis of Variance.

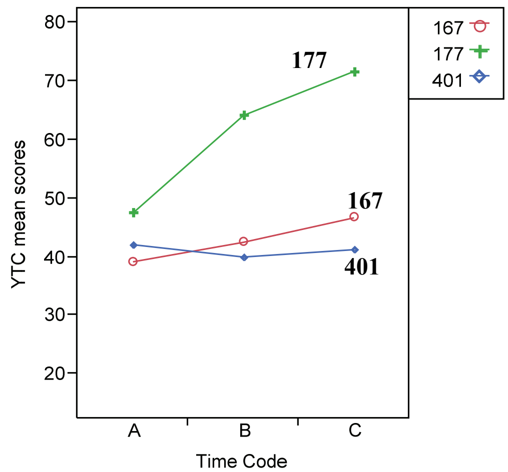
Source	DF	Sum of Squares	Mean Square	F-ratio	Prob>F
Model	8	10753.155	1344.14	7.1087	<0.0001*
Error	81	15315.910	189.09		
C. Total	89	26069.066			

(* Significant at α=.05)

Table 50: Effect Tests for course and time on total YTC score.

Source	DF	Sum of Squares	F-ratio	Prob>F
Course	2	7388.545	19.5376	<0.0001*
Time	2	1598.406	4.2267	0.0179 *
Course*Time	4	1766.203	2.3352	0.0625

Figure 2: Response variable YTC score average against course and time of semester from which the reports were drawn.



Time Code – A: Beginning of Semester; B: Middle of Semester; C: End of Semester.

With more groups involved the chance of committing a Type I error increases (rejecting the null hypothesis when it is true). Tukey's honestly significant difference (HSD) is a conservative test. Tukey's HSD depends on the variation of t-distribution and considers the number of means being covered. Tukey's HSD test is done for a pair-wise comparison of the means. The critical value is denoted as $q_{\alpha}(t,df)$, Tukey's W can be calculated to declare any two pairs of means to be statistically significantly different if they differ by value greater than Tukey's W. In other words $W= q_{\alpha}(t,df)\sqrt{MSW/n}$, where t=t-value, df=degrees of freedom; MSW=within group mean square and n=number of observations. With Tukey's HSD some power is lost when ascertaining a 0.05 experiment-wise Type I error rate (Freund, Wilson & Mohr, 2010). A summary of least square mean differences for Tukey's HSD is given in Table 51 and Table 52 further indicated the means that are statistically different being connected by different letters. For example mean YTC scores for Chem177L during the second month of the semester significantly differ from mean YTC score of Chem167L reports during the second month of the semester. Likewise, the mean YTC score for

Chem177L reports during the third month of the semester is significantly different from the mean YTC scores during the second month of the semester.

Table 51: Least square mean differences Tukey HSD.

Mean[i]-Mean[j] Std Err Dif Lower CL Dif Upper CL Dif	167,A	167,B	167,C	177,A	177,B	177,C	401,A	401,B	401,C
167,A	0	-3.3333	-7.5001	-8.333	-24.999	-32.5	-2.9167	-0.8332	-2.0834
	0	6.14956	6.14956	6.14956	6.14956	6.14956	6.14956	6.14956	6.14956
	0	-22.933	-27.1	-27.933	-44.599	-52.1	-22.517	-20.433	-21.683
	0	16.2667	12.0999	11.267	-5.3991	-12.9	16.6833	18.7668	17.5166
167,B	3.3333	0	-4.1668	-4.9997	-21.666	-29.167	0.4166	2.5001	1.2499
	6.14956	0	6.14956	6.14956	6.14956	6.14956	6.14956	6.14956	6.14956
	-16.267	0	-23.767	-24.6	-41.266	-48.767	-19.183	-17.1	-18.35
	22.9333	0	15.4332	14.6003	-2.0658	-9.5666	20.0166	22.1001	20.8499
167,C	7.5001	4.1668	0	-0.8329	-17.499	-25	4.5834	6.6669	5.4167
	6.14956	6.14956	0	6.14956	6.14956	6.14956	6.14956	6.14956	6.14956
	-12.1	-15.433	0	-20.433	-37.099	-44.6	-15.017	-12.933	-14.183
	27.1001	23.7668	0	18.7671	2.10097	-5.3998	24.1834	26.2669	25.0167
177,A	8.333	4.9997	0.8329	0	-16.666	-24.167	5.4163	7.4998	6.2496
	6.14956	6.14956	6.14956	0	6.14956	6.14956	6.14956	6.14956	6.14956
	-11.267	-14.6	-18.767	0	-36.266	-43.767	-14.184	-12.1	-13.35
	27.933	24.5997	20.4329	0	2.93387	-4.5669	25.0163	27.0998	25.8496
177,B	24.9991	21.6658	17.499	16.6661	0	-7.5008	22.0824	24.1659	22.9157
	6.14956	6.14956	6.14956	6.14956	0	6.14956	6.14956	6.14956	6.14956
	5.39913	2.06583	-2.101	-2.9339	0	-27.101	2.48243	4.56593	3.31573
	44.5991	41.2658	37.099	36.2661	0	12.0992	41.6824	43.7659	42.5157
177,C	32.4999	29.1666	24.9998	24.1669	7.5008	0	29.5832	31.6667	30.4165
	6.14956	6.14956	6.14956	6.14956	6.14956	0	6.14956	6.14956	6.14956
	12.8999	9.56663	5.39983	4.56693	-12.099	0	9.98323	12.0667	10.8165
	52.0999	48.7666	44.5998	43.7669	27.1008	0	49.1832	51.2667	50.0165
401,A	2.9167	-0.4166	-4.5834	-5.4163	-22.082	-29.583	0	2.0835	0.8333
	6.14956	6.14956	6.14956	6.14956	6.14956	6.14956	0	6.14956	6.14956
	-16.683	-20.017	-24.183	-25.016	-41.682	-49.183	0	-17.516	-18.767
	22.5167	19.1834	15.0166	14.1837	-2.4824	-9.9832	0	21.6835	20.4333
401,B	0.8332	-2.5001	-6.6669	-7.4998	-24.166	-31.667	-2.0835	0	-1.2502
	6.14956	6.14956	6.14956	6.14956	6.14956	6.14956	6.14956	0	6.14956
	-18.767	-22.1	-26.267	-27.1	-43.766	-51.267	-21.683	0	-20.85
	20.4332	17.0999	12.9331	12.1002	-4.5659	-12.067	17.5165	0	18.3498
401,C	2.0834	-1.2499	-5.4167	-6.2496	-22.916	-30.417	-0.8333	1.2502	0
	6.14956	6.14956	6.14956	6.14956	6.14956	6.14956	6.14956	6.14956	0
	-17.517	-20.85	-25.017	-25.85	-42.516	-50.016	-20.433	-18.35	0
	21.6834	18.3501	14.1833	13.3504	-3.3157	-10.817	18.7667	20.8502	0

*α=0.050   Q=3.18722,

Table 52: Differences among groups as indicated by Tukey's HSD.

Level				Least Sq Mean
177,C	A			71.666300
177,B	A	B		64.165500
177,A		B	C	47.499400
167,C		B	C	46.666500
167,B			C	42.499700
401,A			C	42.083100
401,C			C	41.249800
401,B			C	39.999600
167,A			C	39.166400

* Levels not connected by the same letter are significantly different.

Effect of Treatment and Time on YTC score

Table 53 shows the ANOVA table and Table 54 shows the interaction effects of types of instruction and which course on the YTC score for student reports. As evident from the effect tests, type of instruction has a significant effect on YTC mean scores $F(1)=39.72$, $p=.0001$ and the time of the semester from which the reports were drawn also impacts YTC scores significantly $F(2)=6.96, p=.0016$. However the effect of time is less significant at $\alpha=.05$. The interaction between type of instruction and time was found to be statistically significantly different for YTC mean scores on critical thinking $F(2)=4.29$, $p=.016$ as there appears to be some interaction between course and time. On slicing the instruction and time and on setting the contrasts it was found that slice guided-inquiry based instruction had a statistical significant effect with $F(2,81)=8.09, P=.0006$; slice time code B (reports from the middle of the semester was significant with $F(1,84)=18.92$, $p=.0001$; and slice time code C (reports from the end of the semester) was significant F(1,84)=27.67,p=.0001 (Table 54, Figure 3).

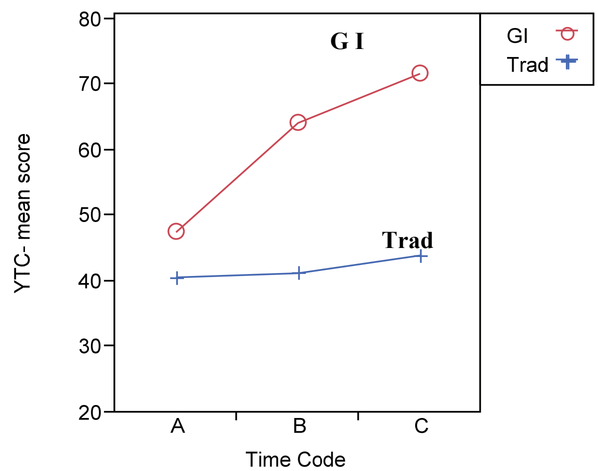
Table 53: Analysis of variance.

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Model	5	10532.664	2106.53	11.3893	<.0001*
Error	84	15536.402	184.96		
Total	89	26069.066			

Table 54: Effect tests for treatments and time on total YTC score.

Source	DF	Sum of Squares	F Ratio	Prob > F
Instruction	1	7346.8772	39.7220	<.0001*
Time Code	2	2576.6111	6.9654	0.0016*
Instruction*Time Code	2	1587.3799	4.2912	0.0168*

Figure 3: Response variable YTC score average against treatment and time of semester from which the reports were drawn.



An analysis of LS means based on Tukey's HSD (Table 55 and Table 56) suggests statistical significant pair-wise differences among means at α=.05. The reports for students who received guided-inquiry based instruction differ significantly on YTC mean scores during the third month of the semester as compared to student reports for guided-inquiry based instruction during the first month of the semester. There were also statistically significant differences in YTC critical thinking means of students who received guided-inquiry based instruction for the reports they wrote during the second month of the semester as compared to laboratory reports written by students receiving traditional instruction during the first, second and third month of the semester. Students receiving guided-inquiry based instruction differed significantly in YTC score means for their reports in the second and third month as compared to YTC score means of the students receiving traditional instruction during the second month of the semester.

Table 55: LS mean differences Tukey HSD.

Mean[i]-Mean[j] Std Err Dif Lower CL Dif Upper CL Dif	GI,A	GI,B	GI,C	Trad,A	Trad,B	Trad,C
GI,A	0	-16.666	-24.167	6.87465	6.24975	3.54125
	0	6.08206	6.08206	5.26722	5.26722	5.26722
	0	-34.405	-41.906	-8.4874	-9.1123	-11.821
	0	1.0725	-6.4283	22.2367	21.6118	18.9033
GI,B	16.6661	0	-7.5008	23.5407	22.9159	20.2074
	6.08206	0	6.08206	5.26722	5.26722	5.26722
	-1.0725	0	-25.239	8.17867	7.55377	4.84527
	34.4047	0	10.2378	38.9028	38.2779	35.5694
GI,C	24.1669	7.5008	0	31.0416	30.4167	27.7082
	6.08206	6.08206	0	5.26722	5.26722	5.26722
	6.4283	-10.238	0	15.6795	15.0546	12.3461
	41.9055	25.2394	0	46.4036	45.7787	43.0702
Trad,A	-6.8747	-23.541	-31.042	0	-0.6249	-3.3334
	5.26722	5.26722	5.26722	0	4.30066	4.30066
	-22.237	-38.903	-46.404	0	-13.168	-15.876
	8.48743	-8.1787	-15.679	0	11.9182	9.20969
Trad,B	-6.2498	-22.916	-30.417	0.6249	0	-2.7085
	5.26722	5.26722	5.26722	4.30066	0	4.30066
	-21.612	-38.278	-45.779	-11.918	0	-15.252
	9.11233	-7.5538	-15.055	13.168	0	9.83459
Trad,C	-3.5413	-20.207	-27.708	3.3334	2.7085	0
	5.26722	5.26722	5.26722	4.30066	4.30066	0
	-18.903	-35.569	-43.07	-9.2097	-9.8346	0
	11.8208	-4.8453	-12.346	15.8765	15.2516	0

**α=0.050 Q=2.91655;LSMean[i] By LSMean[j]

Table 56: Differences among groups as indicated by Tukey's HSD.

Level*				Least Sq Mean
GI,C	A			71.666300
GI,B	A	B		64.165500
GI,A		B	C	47.499400
Trad,C			C	43.958150
Trad,B			C	41.249650
Trad,A			C	40.624750

* Levels not connected by the same letter are significantly different.

Effect of Time and course on Hoyo score

Table 57 shows the ANOVA table and Table 58 shows the interaction effects of time and course on the Hoyo mean scores on critical thinking for student reports. As evident from the effect tests, the type of course has a significant effect on Hoyo mean scores $F(2)=18.20$, $p=.0001$. However the time of the semester from which the reports were drawn does not show any significant effect on the Hoyo mean scores $F(2)=2.22, p=.11$ at $\alpha=.05$. Also there appears to be no interaction or relation between type of course and time on the mean scores for the Hoyo rubric $F(4)=1.99$, $p=.10$. On slicing (simple-simple effects), the type of course and time and on setting the contrasts it was found that only the slice for Chem177L had a significant effect with $F(2,81)=5.80, P=.0044$ among the three courses; the slice for time code B (reports from the middle of the semester was statistically significant with $F(2,81)=9.44$, $p=.0002$; and the slice for time code C (reports from the end of the semester) was significant $F(2,81)=11.69, p=.0001$ (Figure 4).

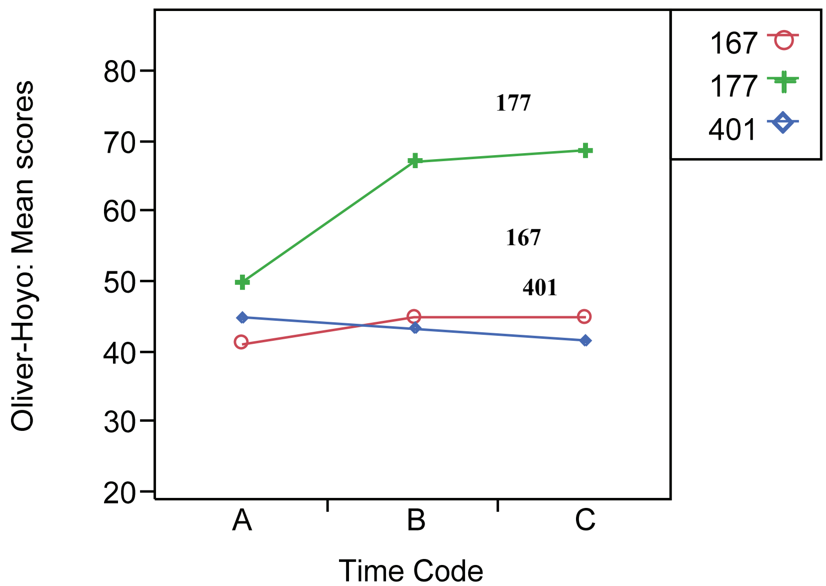
Table 57: Analysis of variance.

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Model	8	9204.243	1150.53	6.1060	<.0001*
Error	81	15262.451	188.43		
C. Total	89	24466.694			

Table 58: Effect tests for course and time on mean Hoyo score.

Source	DF	Sum of Squares	F Ratio	Prob > F
Course work	2	6860.9184	18.2059	<.0001*
Time Code	2	840.2314	2.2296	0.1141
Course work *Time Code	4	1503.0932	1.9943	0.1032

Figure 4: Response variable Hoyo score average against course and time of semester from which the reports were drawn.



A summary of least square mean differences for Tukey's HSD is given in Table 59 and Table 60 further indicated the means that are statistically different being connected by different letters. For example mean Hoyo critical thinking scores for Chem177L reports during the second month of the semester significantly differ from mean Hoyo scores of Chem167L reports during the first, second and third month of the semester. Similarly, the mean Hoyo critical thinking score for Chem177L reports during the third month of the semester is significantly different from the mean Hoyo scores during the first, second and third month of the semester.

Table 59: LS mean differences Tukey HSD.

Mean[i]-Mean[j] Std Err Dif Lower CL Dif Upper CL Dif	167,A	167,B	167,C	177,A	177,B	177,C	401,A	401,B	401,C
167,A	0	-3.8887	-3.8917	-8.8924	-26.114	-27.779	-3.8925	-2.2261	-0.5598
	0	6.13882	6.13882	6.13882	6.13882	6.13882	6.13882	6.13882	6.13882
	0	-23.454	-23.457	-28.458	-45.68	-47.345	-23.458	-21.792	-20.126
	0	15.677	15.674	10.6733	-6.5485	-8.2134	15.6732	17.3396	19.0059
167,B	3.8887	0	-0.003	-5.0037	-22.226	-23.89	-0.0038	1.6626	3.3289
	6.13882	0	6.13882	6.13882	6.13882	6.13882	6.13882	6.13882	6.13882
	-15.677	0	-19.569	-24.569	-41.791	-43.456	-19.57	-17.903	-16.237
	23.4544	0	19.5627	14.562	-2.6598	-4.3247	19.5619	21.2283	22.8946
167,C	3.8917	0.003	0	-5.0007	-22.223	-23.887	-0.0008	1.6656	3.3319
	6.13882	6.13882	0	6.13882	6.13882	6.13882	6.13882	6.13882	6.13882
	-15.674	-19.563	0	-24.566	-41.788	-43.453	-19.567	-17.9	-16.234
	23.4574	19.5687	0	14.565	-2.6568	-4.3217	19.5649	21.2313	22.8976
177,A	8.8924	5.0037	5.0007	0	-17.222	-18.887	4.9999	6.6663	8.3326
	6.13882	6.13882	6.13882	0	6.13882	6.13882	6.13882	6.13882	6.13882
	-10.673	-14.562	-14.565	0	-36.788	-38.452	-14.566	-12.899	-11.233
	28.4581	24.5694	24.5664	0	2.34393	0.67903	24.5656	26.232	27.8983
177,B	26.1142	22.2255	22.2225	17.2218	0	-1.6649	22.2217	23.8881	25.5544
	6.13882	6.13882	6.13882	6.13882	0	6.13882	6.13882	6.13882	6.13882
	6.54847	2.65977	2.65677	-2.3439	0	-21.231	2.65597	4.32237	5.98867
	45.6799	41.7912	41.7882	36.7875	0	17.9008	41.7874	43.4538	45.1201
177,C	27.7791	23.8904	23.8874	18.8867	1.6649	0	23.8866	25.553	27.2193
	6.13882	6.13882	6.13882	6.13882	6.13882	0	6.13882	6.13882	6.13882
	8.21337	4.32467	4.32167	-0.679	-17.901	0	4.32087	5.98727	7.65357
	47.3448	43.4561	43.4531	38.4524	21.2306	0	43.4523	45.1187	46.785
401,A	3.8925	0.0038	0.0008	-4.9999	-22.222	-23.887	0	1.6664	3.3327
	6.13882	6.13882	6.13882	6.13882	6.13882	6.13882	0	6.13882	6.13882
	-15.673	-19.562	-19.565	-24.566	-41.787	-43.452	0	-17.899	-16.233
	23.4582	19.5695	19.5665	14.5658	-2.656	-4.3209	0	21.2321	22.8984
401,B	2.2261	-1.6626	-1.6656	-6.6663	-23.888	-25.553	-1.6664	0	1.6663
	6.13882	6.13882	6.13882	6.13882	6.13882	6.13882	6.13882	0	6.13882
	-17.34	-21.228	-21.231	-26.232	-43.454	-45.119	-21.232	0	-17.899
	21.7918	17.9031	17.9001	12.8994	-4.3224	-5.9873	17.8993	0	21.232
401,C	0.5598	-3.3289	-3.3319	-8.3326	-25.554	-27.219	-3.3327	-1.6663	0
	6.13882	6.13882	6.13882	6.13882	6.13882	6.13882	6.13882	6.13882	0
	-19.006	-22.895	-22.898	-27.898	-45.12	-46.785	-22.898	-21.232	0
	20.1255	16.2368	16.2338	11.2331	-5.9887	-7.6536	16.233	17.8994	0

**α=0.050; Q=3.18722; LSMean[i] By LSMean[j]

Table 60: Differences among groups as indicated by Tukey's HSD.

Level *			Least Sq Mean
177,C	A		68.885500
177,B	A		67.220600
177,A	A	B	49.998800
401,A		B	44.998900
167,C		B	44.998100
167,B		B	44.995100
401,B		B	43.332500
401,C		B	41.666200
167,A		B	41.106400

* Levels not connected by same letter are significantly different.

Effect of treatment and time on Hoyo score

Table 61 shows the ANOVA table and Table 62 shows the interaction effects of type of instruction and course on the Hoyo mean score for critical thinking for student reports. As evident from the effect tests instruction has a statistically significant effect on Hoyo mean score F(1)=37.39, p=.000. The time of semester from which the reports were drawn also impacts the Hoyo scores statistically significantly F(2)=4.26, p=.017. The effect of time is less significant at α=.05 as compared to the effect of instruction. The interaction between instruction and time was found to be significantly different for the mean score on F(2)=3.70, p=.028. There appears to be some interaction between type of course and time of the semester. On slicing the type of instruction and time of the semester and on setting the contrasts it was found that the slice for guided-inquiry based instruction had a statistically significant effect with F(2,84)=5.96, P=.0038 as compared to the slice for traditional instruction F(2,84)=.036, p=0.96. The slice for time of semester code A (reports from the first month of the semester) was not statistically significant F(1,84)=1.75, p=0.18; the slice for time code B (reports from the middle of the semester) was statistically significant with F(1,84)=19.32, p=.0001; and the slice for the time code C (reports from the end/ third month of semester) was statistically significant F(1,84)=23.73, p=.0001 (Figure 5).

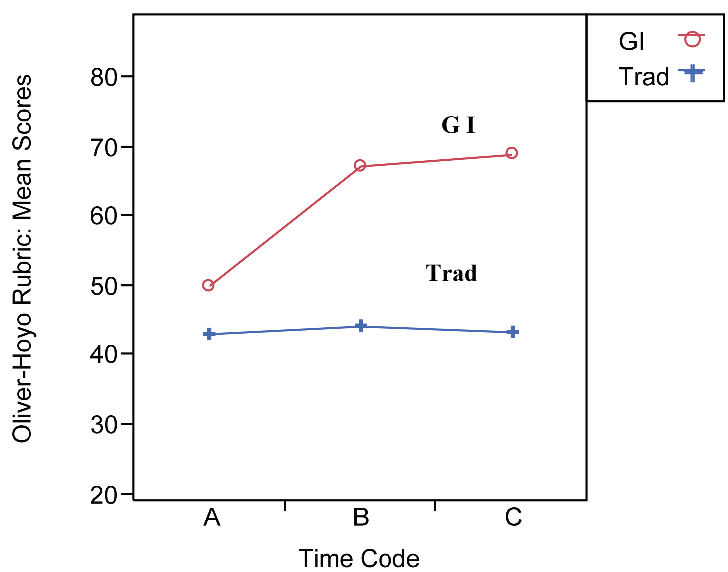
Table 61: Analysis of variance.

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Model	5	9059.156	1811.83	9.8779	<.0001*
Error	84	15407.538	183.42		
C. Total	89	24466.694			

Table 62: Effect Tests for treatments and time on mean Hoyo score.

Source	DF	Sum of Squares	F Ratio	Prob > F
Treatment	1	6858.8944	37.3938	<.0001*
Time Code	2	1564.7435	4.2654	0.0172*
Treatment*Time Code	2	1360.0304	3.7074	0.0286*

Figure 5: Response variable Hoyo score average treatment and time of semester from which the reports were drawn.



An analysis of LS means based on Tukey's HSD (Table 63 and Table 64) suggests statistically significant pair-wise differences among means at the α=.05 level. The reports for students who received guided-inquiry based instruction differ statistically significantly on

Hoyo critical thinking mean score during the second month of semester as compared to student reports for guided-inquiry based instruction during the first month of the semester. There were also statistically significant differences in Hoyo critical thinking mean score of students who received guided-inquiry based instruction for the reports they wrote during the second month of the semester as compared to laboratory reports written by traditionally instructed students during the first, second and third month of the semester. Students receiving guided-inquiry based instruction show significant differences for pair-wise comparison of means.

Table 63: LS mean differences Tukey HSD.

Mean[i]-Mean[j] Std Err Dif Lower CL Dif Upper CL Dif	GI,A	GI,B	GI,C	Trad,A	Trad,B	Trad,C
GI,A	0 0 0 0	-17.222 6.05678 -34.887 0.44309	-18.887 6.05678 -36.552 -1.2218	6.94615 5.24533 -8.3521 22.2444	5.835 5.24533 -9.4632 21.1332	6.66665 5.24533 -8.6316 21.9649
GI,B	17.2218 6.05678 -0.4431 34.8867	0 0 0 0	-1.6649 6.05678 -19.33 16	24.168 5.24533 8.86971 39.4662	23.0568 5.24533 7.75856 38.355	23.8885 5.24533 8.59021 39.1867
GI,C	18.8867 6.05678 1.22181 36.5516	1.6649 6.05678 -16 19.3298	0 0 0 0	25.8328 5.24533 10.5346 41.1311	24.7217 5.24533 9.42346 40.0199	25.5533 5.24533 10.2551 40.8516
Trad,A	-6.9462 5.24533 -22.244 8.35209	-24.168 5.24533 -39.466 -8.8697	-25.833 5.24533 -41.131 -10.535	0 0 0 0	-1.1112 4.28279 -13.602 11.3798	-0.2795 4.28279 -12.77 12.2115
Trad,B	-5.835 5.24533 -21.133 9.46324	-23.057 5.24533 -38.355 -7.7586	-24.722 5.24533 -40.02 -9.4235	1.11115 4.28279 -11.38 13.6021	0 0 0 0	0.83165 4.28279 -11.659 13.3226
Trad,C	-6.6667 5.24533 -21.965 8.63159	-23.888 5.24533 -39.187 -8.5902	-25.553 5.24533 -40.852 -10.255	0.2795 4.28279 -12.211 12.7705	-0.8317 4.28279 -13.323 11.6593	0 0 0 0

Table 64: Differences among groups as indicated by Tukey's HSD.

Level *				Least Sq Mean
GI,C	A			68.885500
GI,B	A	B		67.220600
GI,A		B	C	49.998800
Trad,B			C	44.163800
Trad,C			C	43.332150
Trad,A			C	43.052650

* Levels not connected by the same letter are significantly different.

Inter-rater reliability

In order to assess whether the ratings assigned to the laboratory reports were appropriate, inter-rater reliability was established using Pearson's *r* and Spearman's ρ for pair-wise correlations between the raters. The basic difference between the two statistical tests is that with Pearson's *r* the assumption is that the rating is continuous whereas with Spearman's ρ, the assumption is that the rating is ordinal. The Spearman's correlation coefficient is computed by assigning ranks to the data values instead of using the values themselves.

a) The YTC rubric

For the YTC rubric, an analysis of 18 reports (6 from Chem 167L, 177L and 401L) indicate that the means and the standard deviations are close for the two raters as seen in Table 65. Both graded the reports independently (r = 0.8483). The scoring of the laboratory reports shows positive correlation between the two raters for the mean score on the YTC rubric (Table 66). The non-parametric Spearman's correlation value for the scores (ρ=0.8404) assigned by the two raters using the YTC rubric (Table 67) is in agreement with the values for the Pearson's *r*.

Table 65: Means and standard deviations for inter-rater reliability.

Column	N	DF	Mean	Std Dev	Sum	Minimum	Maximum
YTC Average Score R1	18	17.00	49.7681	17.7627	895.826	29.1660	87.5000
YTC Average Score R2	18	17.00	45.3696	11.2429	816.653	25.0000	66.6660

Table 66: Inter-rater reliability correlations.

	YTC Average Score R1	**YTC Average Score R2**
YTC Average Score R1	1.0000	0.8483
YTC Average Score R2	0.8483	1.0000

Table 67: Non-parametric Spearman's correlation.

Variable	by Variable	Spearman ρ	Prob>|ρ|
YTC Total Score Scaled for 100 R2	YTC Total Score Scaled for 100 R1	0.8404	<.0001*

b) The Hoyo rubric

For Hoyo rubric the ratings between the two raters were compared for 18 laboratory reports. A second rater scored six laboratory reports per course (Chem167L, 177L and 401L). A total of 18 laboratory reports were scored as a subset by the two raters. Table 68 provides the mean values and standard deviations for scores assigned by the two raters on the 18 laboratory reports. The mean values for the two raters are very close (For R1: M=51.54; S, D=17.23 and for R2: M=52.15; S. D.=12.22 , r=0.8538 (Table 69). The scoring of the laboratory reports shows a positive Spearman correlation (ρ=0.790) between the two raters for the mean score on the Hoyo rubric (Table 70).

Table 68: Means and standard deviations for inter-rater reliability.

Column	N	DF	Mean	Std Dev	Sum	Minimum	Maximum
Hoyo Average Score R1	18	17.00	51.5407	17.2354	927.732	33.3300	88.8880
Hoyo Average Score R2	18	17.00	52.1589	12.2232	938.861	33.3300	72.2220

Table 69: Inter-rater reliability correlations.

	Hoyo Average Score R1	Hoyo Average Score R2
Hoyo Average Score R1	1.0000	0.8538
Hoyo Average Score R2	0.8538	1.0000

Table 70: Non-parametric Spearman's correlation.

Variable	By Variable	Spearman ρ	Prob>|ρ|
Hoyo Average Score R2	Hoyo Average Score R1	0.7901	<.0001*

Conclusion(s)

This study was begun in hopes of being able to answer two research questions. The first research question for this quantitative study was to determine whether the students experiencing guided-inquiry instruction in the laboratory were better critical thinkers than those students who instead use a traditional approach.

In order to answer this research question two rubrics were used to assess critical thinking based on students' written work. The first rubric used was developed by York Technical College (YTC – critical thinking rubric). The second rubric was developed by a chemical education researcher Maria Oliver-Hoyo to assess student written work in the form of laboratory reports and to evaluate improvement in student critical thinking skills during the implementation of a guided-inquiry (GI) based chemistry course for freshmen. Both rubrics were used because they both had six different traits related to the stages of critical thinking. It was found that on a qualitative level, both of these rubrics were similar for the traits of critical thinking skills. Rubrics were modified to a very small extent in order to accommodate the freshmen student laboratory report formats (which do not have an abstract section) but the title or purpose in traditional format and title and beginning questions in the case of reports in the SWH format. A baseline comparison was done for student scores on their first lab reports in the two groups and no statistically significant differences were found between the scores for reports in the GI-based group (N=10, M=56.56, S.D.=7.94) as compared to traditional reports (N=20, M=61.03, S.D.=16.41, t(28)=1.003, p=0.032, d=1.10, r=0.48).

The laboratory reports of students were scored independently for the two rubrics. Mean scores were calculated for reports for students in both the instructional approaches for each of the six traits for reports of students who received guided-inquiry based instruction and students who received traditional instruction. Based on the YTC rubric it was found that the student report mean scores on critical thinking for the guided-inquiry based group were statistically significantly higher ($N=30$; $M=14.66$; $S.D.=3.35$) compared to the student reports in the traditional group ($N=60$; $M=10.06$; 3.56, $t(61.4)=-5.99$, $p=.0001$, $d=1.32$, $r=0.55$). Based on the Hoyo rubric, averages for the laboratory reports for students who received guided-inquiry based instruction were statistically significantly higher for the mean of various traits of critical thinking ($N=30$; $M=11.16$; $S.D.=2.85$) as compared to laboratory report scores of students who experienced traditional instruction ($N=60$, $M=7.83$; $S.D.=2.38$, $t(48)=-5.51$, $p=.0001$, $d=1.26$,$r=0.53$).

The second research question was about the comparison of critical thinking scores of laboratory reports of students who received guided-inquiry based instruction among different groups. With a goal to determine whether there was any difference between critical thinking scores of students at (a) at freshmen level and advanced chemistry students (b) and among mean critical thinking scores on laboratory reports for the courses chemistry 167L, 177L and 401L. To answer the first part of the question a t-test was done to compare for the mean critical thinking score of students laboratory reports at the freshmen level and the advanced level (seniors). For the YTC rubric it was found that the mean report scores for students at the freshmen level were statistically significantly higher ($N=60$; $M=12.46$; $S.D.=4.05$) than student laboratory report critical thinking scores at the advanced level of chemistry ($N=30$; $M=9.86$; $S.D.=3.70$; $t(63)=-3.04$, $p=0.0034$; $d=0.66$; $r=0.32$. When testing for difference in the mean score on critical thinking based on the Hoyo rubric, a similar trend was found. The laboratory reports for freshmen students received a statistically significantly higher score (N=60; M=9.52; S.D.=3.06) as compared to laboratory reports for advanced chemistry students (N=30; m=7.80; S.D.=2.48; t(70)=-2.85; p=0.0057, d=0.61; r=0.29).

To answer the second part of the question an F-test was conducted to see whether there were any differences in the mean scores for critical thinking for laboratory reports from each laboratory course in the study. Based on an F-test, statistically significant differences were found for mean scores for critical thinking according to the YTC rubric F(2,87)=17.2, p=<.0001. Based on Tukey-HSD post-hoc comparisons for each pair of means, it was found that the mean score for critical thinking for laboratory reports for Chem177L was found to be statistically significantly higher (M=14.6; S.D.=3.35, as compared to Chem167L (M=10.26, S.D.=3.48; p=.0001). Between the 177L and 401L pairs, it was found that the mean score for the Chem177L reports (M=14.66; S.D.=3.35) was statistically significantly higher than the mean score for critical thinking for Chem401L laboratory reports (M=9.86; S.D.=3.70, p=.0001). There were no statistically significant differences between the means in critical thinking scores for the pairs Chem177L and Chem401L. (p=0.898). The critical thinking scores were compared on the laboratory reports for the three courses based on Hoyo rubric using an F-test. The F-test indicates a statistically significant difference among the mean critical thinking scores for the three courses F(2,87)=16.9;p=<.0001. On comparing mean scores using Tukey's HSD, it was found that the pair of Chem177L (M=11.16, S.D.=2.85) and Chem401L was statistically significantly different (M=7.80, S.D.=2.48; P=.0001).The Chem177L mean score (M=11.16, S.D.=2.85) differs statistically significantly from Chem167L (7.86, S.D.=2.31, p=.0001). There were no statistically significant differences found between the Chem167L and Chem401L for mean scores for critical thinking for laboratory reports for the Hoyo rubric.

The third research question is about the correlation between the YTC and the Hoyo rubrics. In order to answer this research question a comparison was made between YTC and Hoyo rubric mean scores scaled to a total score of 100 (each laboratory report initially was awarded a total score of 24 on the YTC rubric and a total score of 18 on the Hoyo rubric. First, the percent score for each report were calculated and then the means for the YTC and Hoyo rubrics were calculated. Several correlations were performed for both the YTC and the Hoyo rubric. Based on the correlation studies for each of the groups positive correlation was found between the YTC and the Hoyo rubrics for the different courses in study and for different times of the semester from which the reports were drawn. Positive correlation (>0.88) of mean scores on various traits of critical thinking for multiple comparisons indicates that the two rubrics are in agreement with the various traits of critical thinking.

The last research question for this study was to find whether there were any interactions between the variables involved. It was of interest to determine whether it is only an instructional approach that impacts critical thinking (as reflected in student laboratory report writing) or whether there is an interaction between the course and the time from which the laboratory reports were drawn. In other words, are the mean YTC and Hoyo rubric scores dependent only on instruction or do other factors like time and course have a contribution? In order to determine whether there was any interaction between time of semester from which the laboratory reports were drawn and the instructional approach (treatment) used, a two-way ANOVA analysis and subsequent Posthoc comparisons for the pair of means were performed. The effects (simple-simple effects) were sliced to see which effect was significant on mean score for critical thinking for the YTC as well as the Hoyo rubrics. In the case of the YTC rubric, it was found that the course [$F(2)=19.53, p=.0001$] and time [$F(2)=4.22$; $p=0.017$] during which the reports were drawn had a significant effect on the mean score. There was no evidence of interaction between course and time [$F(4)=2.33$, $p=0.062$]. For the Hoyo rubric it was found that the course had a significant effect [$F(2)=18.2$; $p=.0001$]; the time of the semester from which the reports were drawn did not affect the Hoyo mean score [$F(2)=2.22$; $p=0.11$]. The interaction between the time and course was not statistically significant [$F(4)=1.99$; $p=0.10$]. The least-square mean differences using Tukey Kramer's HSD at $\alpha=0.05$ showed a pair of means that were statistically significantly different (Chem177L mean score for reports drawn from first month were different from Chem167L and Chem401L reports drawn during the first month).

For the effect tests of interaction between time and treatment used (instructional approach) it was earlier found that the instructional approach, namely the guided-inquiry based laboratory reports had statistically significantly higher means. When specifically looking at the effects using a two-way ANOVA, it was found that instructional approach [$F(1)= 39.7$, $p=.0001$] showed a statistically significant effect for reports drawn from the three time frames [$F(2)=6.96$, $p=0.0016$] during the semester (first month, second month and third month). The interaction between the instructional approach used and the reports drawn from different time frames or periods during the semester was significant for YTC mean scores [$F(2)=4.29$; $p=0.0168$]. The Hoyo mean score for laboratory reports also indicated a statistically significant effect of instructional approach used [$F(1)=37.39$; $p=.0001$] and the time from which the reports were drawn during the semester [$F(2)=4.26$; $p=0.017$]. The effect test showed significant interaction between the instructional approach and the time effects [$F(2)=3.70$; $p=0.028$] for the Hoyo mean score on laboratory reports.

Based on the findings of this study on the critical thinking abilities of students as assessed from their written laboratory reports, it can be concluded that:

1. The instructional approach has a significant effect on critical thinking as analyzed based on the YTC and the Hoyo rubrics used for the analysis of students' written work. Students who were instructed using the guided-inquiry based Science Writing Heuristic approach had statistically significantly higher means using both the rubrics as compared to students who experienced a traditional instruction approach laboratory reports.
2. As students progressed during the semester, student critical thinking abilities improve statistically significantly in the case of guided-inquiry based instructions for freshmen students and slightly in the case of engineering students who received traditional instruction.
3. Freshmen general chemistry students who received instruction using the guided-inquiry based teaching approach performed statistically significantly better on critical thinking scores for the YTC and the Hoyo rubrics as compared to freshmen chemistry students whose instruction used a traditional approach, and for advanced chemistry students who received traditional laboratory instruction.

Limitations

This study had its own limitations. Several tests were performed to ascertain that the findings were consistent. However, there was a limitation of data. Data included student laboratory report scores and copies of student laboratory reports. It would have been worthwhile to interview students from all the groups on a set of problems to see whether there were any differences between the students at the two levels of chemistry who were instructed using guided-inquiry based instruction and traditional instruction. There were also only two effective SWH teaching assistants. So data collection was limited to the reports of the students of these two teaching assistants for fair comparison. It was difficult to explore gender differences with a relatively small number of females in the study. The reports drawn for selected Chem167L were for males and there was only one female enrolled in the Chem401L group during the study.

Further studies

For further research on assessment of critical thinking based on student written work, the suggestion would be doing in-depth qualitative analysis of student reports using Toulmin coding. To further support quantitative findings, qualitative data may be used to present the quality of student scientific arguments on the laboratory activities selected for the study. It will be good to conduct student interviews at various points during the semester to connect their understanding of concepts and principles on various laboratory experiments and further compare the students at the two levels of chemistry – the freshmen and the advanced chemistry students. It will also be worthwhile to study the differences among the different levels of instructor implementation of the Science Writing Heuristic approach (high, medium and low) and its comparison with student written reports for traditional students at the freshmen and advanced levels of chemistry.

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CHAPTER 5

CONCLUSIONS

General Conclusions

This dissertation explores the impact of chemistry laboratory instruction. Through the research on problem solving, implementing student roles during a guided-inquiry based Science Writing Heuristic approach and by studying the impact of laboratory instruction on critical thinking skills of students there appears to be an association between the laboratory instruction and students' problem solving skills. In addition, laboratory instruction leads to a positive attitude for chemistry among students and improves their critical thinking skills. Critiques of laboratory instruction in chemistry have argued that laboratories don't serve current pedagogical needs, involve time and resources on the part of instructors, and have even suggested that general chemistry laboratories should be completely eliminated for some majors.

The research studies reported in this work were focused on different aspects of laboratory instruction. The premise for the first study questioned whether laboratory instruction has an impact on student attitude toward general chemistry and their academic performance based on their problem solving ability in the areas of stoichiometry and thermochemistry. It was found that laboratories have a statistically significant effect on student attitudes, their logical thinking skills as well as their problem solving. In this study, 40 students were interviewed out of whom 18 students were enrolled in a general chemistry laboratory course concurrently with a lecture course. Students were specifically interviewed about topics that were studied during the two general chemistry courses in the research study-General Chemistry 167, General Chemistry 167L, and General Chemistry 177/General Chemistry 177L. Students who took a concurrent laboratory and lecture course had significantly better understanding of the problem as compared to students who were taking only the lecture component of the course. In addition students enrolled in both the lecture and the laboratory component displayed significantly better attitudes toward chemistry as compared to the students enrolled only in the lecture.

The next study is on implementing student roles while implementing the guided-inquiry based Science Writing Heuristic approach. Previous studies have shown improved academic performance of students when implementing the Science Writing Heuristic approach. The studies have also shown a positive correlation between the level of effectiveness of implementation of the Science Writing Heuristic approach by the instructor in a general chemistry laboratory and its effect on student academic performance during the lecture component of the general chemistry course. However, researchers in prior studies have also mentioned that roughly 4-6 weeks are required for instructors to be effective at using the SWH approach and in training their students to write their laboratory reports in the SWH format.

The implementation of student roles in Science Writing Heuristic based laboratories led to a new form of implementation of student-centered learning in which students facilitate their learning in laboratory *along with* the instructor. The new approach was called Student-Led Instructor-Facilitated Guided-Inquiry Learning. The approach was developed to address issues with students who are not actively involved in their learning in a laboratory environment and are mostly mute spectators depending on their laboratory partners or the instructor. An approach being inquiry-based does not lend itself to inquiry until it is implemented in a way that it involves the students and not only should they understand the experiments but they should also facilitate the laboratory activities in some shape or form. Implementation of roles served the purpose of engaging each student in the laboratory with the general chemistry experiment each week. As a result of the implementation of student roles, student academic performance showed statistically significant improvement as compared to students who received instructor-facilitated SWH based instruction. Further adopting student roles statistically significantly improved students' quality of laboratory reports in the SWH format, and increased student-student interaction. In addition, students reported being better prepared to work in the laboratory and improved their communication skills.

The last chapter of this dissertation is focused on the impact of guided-inquiry based instruction on the critical thinking abilities of students. In this quantitative study, student laboratory reports were compared. The assumption was that that advanced chemistry students receiving traditional laboratory instruction would have a better understanding of chemistry concepts and principles and hence they would display advanced critical thinking when compared to freshmen general chemistry students who received SWH-based laboratory instruction and write their reports in the SWH format. As a result of this study using two different rubrics on critical thinking skills it was found that the grade level of student had no impact on critical thinking. The study showed that guided-inquiry based students are statistically significantly better critical thinkers.

Future investigations

Laboratory instruction provides a unique opportunity to students to observe macroscopic phenomenon. However, it is worthwhile to investigate different laboratory activities, the impact that each laboratory activity has on student understanding of specific topics of chemistry, and how it helps the students draw connections. In addition, student perceptions of laboratory as a medium of instruction and how it impacts their understanding of different areas of chemistry needs to be studied further. Teaching chemistry in a laboratory does not only require a thorough understanding of the content, but it also requires that instructors are aware of various research-based pedagogical approaches that can be employed to engage students in the laboratory and have a meaningful learning experience. In order to ensure that students are meeting learning outcomes, it is important to set the goals for each laboratory in accordance with the lecture component of the chemistry course so that the laboratories are either (a) coordinated or (b) integrated with the lecture course. Instead of providing student one laboratory experience on a given concept, it is important to have a curriculum that builds on the prior laboratory activities so that students can add to their knowledge base. Instruction is one aspect and learning from a laboratory is another aspect, though both are interrelated. In-depth student interviews on various topics may provide further understanding of the student thinking process about various topics covered during a laboratory curriculum.

In addition, the newer approaches to teaching laboratory should also focus on how technological interventions lead to correct understandings or misconceptions in chemistry. For example are students applying any thinking skills when working on simulations or are they are doing verification in a virtual environment? It is important for researchers to explore how laboratory instruction impacts learners. Do we really need the laboratories with changing times? Do all the students need to enroll in a laboratory course along with the lecture component of chemistry? Do the students transfer the skills acquired during laboratories to other domains that require problem solving and critical thinking? These are some of the questions that are worth exploring to further establish the relevance of laboratory based-chemistry instruction.

APPENDIX A

BAUER'S ASCI v. 2

Name: ______________________ ISU-ID:____________________ Section:____________

A list of opposing words appears below. Rate how well these words describe your feelings about **chemistry**. Think carefully and **try not to include** your feelings toward chemistry teachers or chemistry courses. For each line, choose a position between the two words that describes **exactly how you feel**. Circle that number on this sheet. The middle position is if you are undecided or have no feelings related to the terms on that line.

CHEMISTRY IS

1	easy	1	2	3	4	5	6	7	hard
					middle				
2	complicated	1	2	3	4	5	6	7	simple
3	confusing	1	2	3	4	5	6	7	clear
4	comfortable	1	2	3	4	5	6	7	uncomfortable
5	satisfying	1	2	3	4	5	6	7	frustrating
6	challenging	1	2	3	4	5	6	7	not challenging
7	pleasant	1	2	3	4	5	6	7	unpleasant
					middle				
8	chaotic	1	2	3	4	5	6	7	organized

APPENDIX B

Test of Logical Thinking (TOLT) Instrument

Orange Juice #1

1. Four large oranges are squeezed to make six glasses of juice. How much juice can be made from six oranges?

a) 7 glasses b) 8 glasses c) 9 glasses d) 10 glasses e) other

2. What was the reason for your answer to question 1?

a) The number of glasses compared to the number of oranges will always be in the ratio 3 to 2.
b) With more oranges, the difference will be less.
c) The difference in the numbers will always be two.
d) With four oranges the difference was 2. With six oranges the difference would be two more.
e) There is no way of predicting.

Orange Juice #2

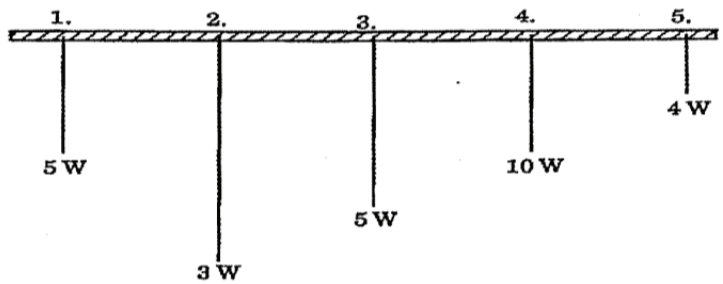
3. How many oranges are needed to make 13 glasses of juice?

a) 6 1/2 oranges b) 8 2/3 oranges c) 9 oranges d) 11 oranges e) other

4. What was the reason for your answer to question 3?

a) The number of oranges compared to the number of glasses will always be in the ratio 2 to 3.
b) If there are seven more glasses, then five more oranges are needed.
c) The difference in the numbers will always be two.
d) The number of oranges will be half the number of glasses.
e) There is no way of predicting the number of oranges.

DO NOT WRITE ON THIS SHEET



The Pendulum's Length

5. Suppose you wanted to do an experiment to find out if changing the length of a pendulum changed the amount of time it takes to swing back and forth. Which pendulums, in the above figure, would you use for the experiment?

a) 1 and 4 b) 2 and 4 c) 1 and 3 d) 2 and 5 e) all

6. What is the reason for your answer to question 5?

a) The longest pendulum should be tested against the shortest pendulum.
b) All pendulums need to be tested against one another.
c) As the length is increased the number of washers should be decreased.
d) The pendulums should be the same length but the number of washers should be different.
e) The pendulums should be different lengths but the number of washers should be the same.

The Pendulum's Weight

7. Suppose you wanted to do an experiment to find out if changing the weight on the end of the string changed the amount of the time the pendulum takes to swing back and forth. Which pendulums, in the above figure, would you use for the experiment?

a) 1 and 4 b) 2 and 4 c) 1 and 3 d) 2 and 5 e) all

8. What was the reason for your answer to question 7?

a) The heaviest weight should be compared to the lightest weight.
b) All pendulums need to be tested against one another.
c) As the number of washers is increased the pendulum should be shortened.
d) The number of washers should be different but the pendulums should be the same length.
e) The number of washers should be the same but the pendulums should be different lengths.

DO NOT WRITE ON THIS SHEET

The Vegetable Seeds

9. A gardener bought a package containing 3 squash seeds and 3 bean seeds.
If just one seed is selected from the package what are the chances that it is a bean seed?

a) 1 out of 2 b) 1 out of 3 c) 1 out of 4 d) 1 out of 6 e) 4 out of 6

10. What was the reason for your answer to question 9?

a) Four selections are needed because the three squash seeds could have been chosen in a row.
b) There are six seeds from which one bean seed must be chosen.
c) One bean seed needs to be selected from a total of three.
d) One half of the seeds are bean seeds.
e) In addition to a bean seed, three squash seeds could be selected from a total of six.

The Flower Seeds

11. A gardener bought a package of 21 mixed seeds. The package contents listed:

3 short red flowers
4 short yellow flowers
5 short orange flowers
4 tall red flowers
2 tall yellow flowers
3 tall orange flowers.

If just one seed is planted, what are the chances that the plant that grows will have red flowers?

a) 1 out of 2 b) 1 out of 3 c) 1 out of 7 d) 1 out of 21 e) other

12. What was the reason for your answer to question 11?

a) One seed has to be chosen from among those that grow red, yellow or orange flowers.
b) 1/4 of the short and 4/9 of the talls are red.
c) It does not matter whether a tall or a short is picked. One red seed needs to be picked from a total of seven red seeds.
d) One red seed must be selected from a total of 21 seeds.
e) Seven of the twenty-one seeds will produce red flowers.

DO NOT WRITE ON THIS SHEET

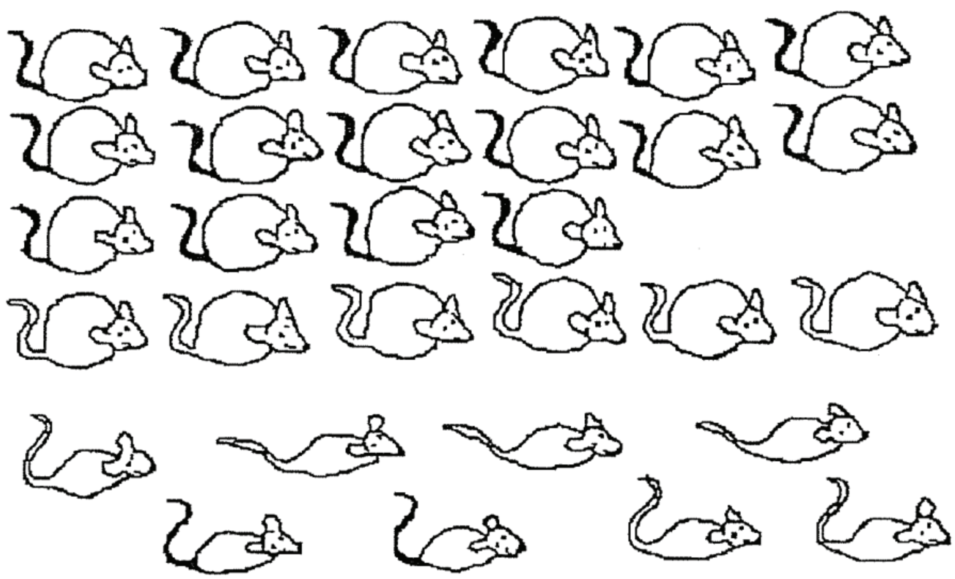
The Mice

13. The mice shown represent a sample of mice captured from a part of a field. Are fat mice more likely to have black tails and thin mice more likely to have white tails?

a) Yes b) No

14. What is the reason for your answer to question 13?

a) 8/11 of the fat mice have black tails and 3/4 of the thin mice have white tails.
b) Some of the fat mice have white tails and some of the thin mice have white tails.
c) 18 mice out of thirty have black tails and 12 have white tails.
d) Not all of the fat mice have black tails and not all of the thin mice have white tails.
e) 6/12 of the white tailed mice are fat.



DO NOT WRITE ON THIS SHEET

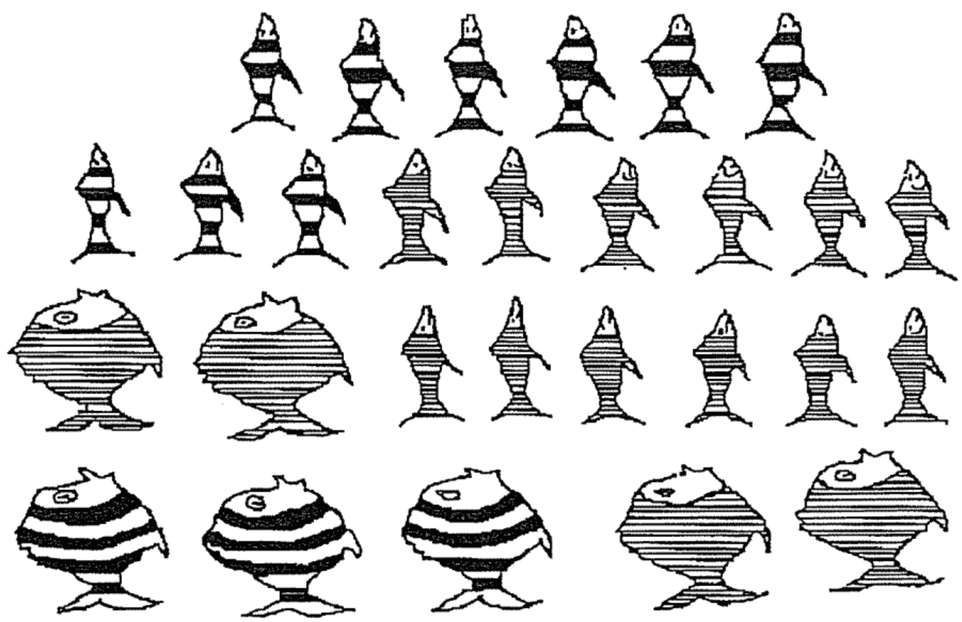
The Fish

15. Are fat fish more likely to have broad stripes than thin fish?

a) Yes b) No

16. What is the reason for your answer to question 15?

a) Some fat fish have broad stripes and some have narrow stripes.
b) 3/7 of the fat fish have broad stripes.
c) 12/28 are broad striped and 16/28 are narrow striped.
d) 3/7 of the fat fish have broad stripes and 9/21 of the thin fish have broad stripes.
e) Some fish with broad stripes are thin and some are fat.



DO NOT WRITE ON THIS SHEET

The Student Council

17. Three students from grade 10, 11, 12 were elected to the student council. A three member committee is to be formed with one person from each grade. All possible combinations must be considered before a decision can be made. Two possible combinations are Tom, Jerry and Dan (TJD) and Sally, Anne and Martha (SAM).

List all other possible combinations in spaces provided on the answer sheet. More spaces are provided on the answer sheet than you will need.

STUDENT COUNCIL

Grade 10	Grade 11	Grade 12
Tom (T)	Jerry (J)	Dan (D)
Sally (S)	Anne (A)	Martha (M)
Bill (B)	Connie (C)	Gwen (G)

The Shopping Center

18. In a new shopping center, 4 store locations are going to be opened on the ground level. A BARBER SHOP (B), a DISCOUNT STORE (D), a GROCERY STORE (G), and a COFFEE SHOP (C) want to move in there. Each one of the stores can choose any one of four locations. One way that the stores could occupy the four locations is BDGC.

List all other possible ways that the stores can occupy the 4 locations. More spaces are provided on the answer sheet than you will need.

DO NOT WRITE ON THIS SHEET

APPENDIX C

GRADING RUBRIC FOR THE INTERVIEW WORKSHEET QUESTIONS

GRADING RUBRIC FOR STOICHIOMETRY PROBLEMS

Problem 1	
No attempt	0
Molecular Formula Ethanol	1
Correct Molar Mass of ethanol 46.04 grams	1
Correct Moles of Ethanol	2
Balanced equation attempted	1
Correct balanced equation	2
Grams of oxygen incorrect	1
Grams of oxygen correct =2.08 grams	2
Total points for problem 1	**6**

Problem 2	
No attempt	0
Balanced equation each entry correct	4
Convert gallons to kilograms or moles or grams correctly	2
Calculated the grams/ kg/ moles of CO_2 formed correctly	2
Calculated the grams/ kg/ moles of H_2O formed correctly	2
Calculated percent efficiency correctly 96-97% correctly	2
Any incorrect calculation from 2-6 above is -1	
Total points for problem 2	**12**

GRADING RUBRIC FOR THERMOCHEMISTRY PROBLEMS

Problem 1	
No attempt	0
Convert gallon to grams	2
Convert to Joules or Kilojoules correctly using the proper conversion factors	2
Correct value of ΔT =7.5 °C	1
Correct value of final temperature = 25 °C	1
Total points for problem 1	**6**

Problem 2 (divided into four parts, 2a, 2b, 2c, 2d)	
Problem 2a	
Correct moles of fat *Tristearin* =0.0135	1
Used information from the balanced equation to calculate the Calories =121.68	2
Used partial information from the problem and multiplied 12 grams with 9 Calories to get an answer 0f 108 Calories	1
Total point for problem 2a	**3**

Problem 2b	
Converts kilograms to grams	1
Converts 200 **Big Calories** to ***small calories*** or from kilojoules to Joules	1
Finds the final temperature to be 58.8 °C correctly	1
Total points for problem 2b	**3**

Problem 2c	
Calculates q as 1591.5 Kilojoules or in Joules	1
Converts KJ or Joules to Calories	1
Final answer correct as 380.4 Calories	1
Total points for problem 2c	**3**

Problem 2d	
Calculates ΔH for gaseous water for 55 moles according to the balanced equation for the metabolism of fat *tristearin*	1
Finds the difference between the ΔH of gaseous water and ΔH of liquid water	1
Finds the value of ΔH as a negative value in the range of 35,000-36,000	1
Total points for problem 2d	3

Total points problem 2 (all 4 parts)	**12**

Overall worksheet points (stoichiometry + thermochemistry)	**36**

APPENDIX D

MATRIX FOR SCORING STUDENT ARGUMENT

Quality of Beginning Questions.

0	1	2	3	4	5
No question.	Single question. Closed-ended question. Unimportant and poor questions. Questions are not testable. Questions does not catch the essence of the investigation. Questions are insignificant. Questions are of low quality.	A few questions. Closed-ended questions. Testable or maybe difficult to test. May not be meaningful questions. Questions may not catch the essence of the investigation. Questions may not be significant and adequate. Questions may be of low quality.	Multiple questions which are primarily closed-ended questions. If only one, it is open-ended question. Meaningful questions. Testable questions. Questions may match the essence of the investigation. Questions may be significant and adequate. Questions may be of high quality.	Multiple questions which include at least one open-ended question. Testable questions. Questions are significant and adequate. Questions catch the essence of the investigation. Questions are of high quality.	Multiple questions which include more than one open-ended question. Testable and scientific questions. Essential questions. Questions catch the essence of the investigation thoroughly. Questions are very significant and adequate. Questions are very of high quality.

Quality of Claims.

0	1	2	3	4	5
No claim.	Single Claim. Claims are not based on any data or observation. Claim does not catch the essence of the investigation. Claim is insignificant. Claim is invalid. Claim is inaccurate. Claim is of low quality.	Single or multiple claims. Claims may not appear to have come from their experimental data. Claims may not catch the essence of the investigation. Claims may not be significant and adequate. Claims may not be valid and sound. Claims may be low quality.	Single or multiple claims. Claims are from their experimental data. Claims may match the essence of the investigation. Claims may be significant and adequate. Claims may be valid and sound. Claims may be of high quality.	Multiple claims. Claims from the interpretation of their experimental data. Claims catch the essence of the investigation. Claims be significant and adequate. Claims be valid and sound. Claims be accurate and high quality.	Multiple claims. Claims are from, and based on, the interpretation of their experimental observation/data (Claims about what they found out?). Claims catch the essence of the investigation thoroughly. Claims are very significant and adequate. Claims are very valid and sound. Claims are very accurate and of high quality.

Relationship between the Beginning Questions and Claims.

0	1	2	3	4	5
No connection (due to no questions or no claims).	Very weak connection between questions and claims. Claims without any questions or questions without any claims. Questions and claims do not fit at all.	Weak connection. Questions and claims fit loosely. Student develops claims for a few of the generated questions. Claims are uncertain in answering questions.	Moderate connection. Questions and claims fit reasonably. Student develops claims for some questions and proposed claims may be apparent in answering questions. Claims are focusing on all the questions but loosely connected with questions.	Strong connection. Questions and claims fit strongly. Student develops claims for most of the generated questions. Proposed claims are evident in answering questions even though claims are only for some generated questions.	Very strong connection. Questions and claims fit very strongly together. Student develops claims for all the generated questions and all the provided claims are obvious in answering questions.

Quality of Evidence.

0	1	2	3	4	5
No evidence.	Very weak evidence. Be inaccurate, invalid, and unreliable evidence. Evidence is very sparse. Their observation is itself evidence *(..., "see my observation.., calculation, or data section*). Evidence seems to come from nowhere in particular.	Weak evidence. May not be accurate, valid, and reliable. Evidence are just a description of data. Evidence are from textbook.	Moderate evidence. May be accurate evidence. May be valid evidence. May be reliable evidence. Evidence from data and textbook with a little interpretation or explanation.	Powerful evidence. Valid evidence. Accurate evidence. Reliable evidence. Evidence from the interpretation of their observation and data collected.	Very powerful evidence. Very valid, accurate, rich evidence. Very credible and reliable evidence. Evidence from interpretation of their data.

Relationship between Claims and Evidence.

0	1	2	3	4	5
No connection (due to no claims or no evidence).	Very weak or no connection between claims and evidence. Evidence is not focusing on the claims at all. Claims without evidence or evidence without claims.	Weak connection. Evidence supports claims loosely or inadequately. Students provide evidence for a few claims. Proposed evidence may not be apparent in supporting claims. Evidence is focusing on a few claims loosely.	Moderate connection. Evidence supports claims reasonably. Students provide evidence for some of the generated claims and proposed evidence may be apparent in supporting claims. Evidence is focusing on all the claims but loosely connected with claims.	Strong connection. Evidence supports claims strongly. Students provide evidence for most of the generated claims. Evidence is clearly supporting claims even though it is about some claims. Evidence is focusing on all the claims and clearly connected with claims.	Very strong connection. Evidence very strongly, effectively, and thoroughly supports all claims. Students provide evidence for all the generated claims. Evidence is very clearly supporting all the claims.

Multiple Representations in Evidence.

0	1	2	3	4	5
No representation.	Mono-mode representations or no representation. Only text.	Bi-mode representations. Text and graph. Text and math equations. Text and chemical equations. Text and diagram.	Tri-mode representations. Three kinds of representations.	Multiple-mode representations. Four kinds of representations.	Multiple-mode representations. Five kinds of representations. Examples: text, math representations, chemical representations, graph, tables, and diagrams.

Reflection.

0	1	2	3	4	5
No reflection.	Very-weak explanation for, why ideas have changed or have not changed?	Weak explanation for, why ideas have changed or have not changed?	Moderate understanding of, why ideas have changed or have not changed?	Strong understanding of why ideas have changed or have not changed?	Thorough explanation for their idea change or no change.
	Student is not able to link their own investigation to their existing knowledge.	Student may not be able to link their own investigation to their existing knowledge.	Student may understand how their investigations tie into concepts about what they have learned in class?	Student understands how their investigations tie into concepts about what they have learned in class?	Student strongly understands how their investigations tie into concepts about what they have learned in class.
			Student may make connections to concepts.	Student makes some connections to concept and real life.	Student refers to some real life application to make a connection with their laboratory work.
	Student does not spot errors.	Student may not spot errors.	Student may spot errors and may not explain them.	Student spot errors and has some explanation for them.	Student has suggestions for correcting their errors.
	Student does not have new questions.	Student may not have new questions.	Students may have new questions.	Student has new questions.	Student recognizes what new things they have to think about.
					Student has new testable questions that are related to the investigation.

The Analytical Framework for Evaluating the Quality of Whole Argument in Student Science Writing with the SWH approach.

1 – 2	3 – 4	5 – 6	7 – 8	9 – 10
Very weak argument.	Weak argument.	Moderate argument.	Powerful/enriched argument.	Very powerful/Enriched argument.
No testable questions, invalid claims, and unreliable evidence.	May not be testable questions, valid claims, and reliable evidence.	May be significant questions, adequate claims, and appropriate evidence.	Significant questions, accurate claims, valid/strong /accurate evidence, and meaningful reflection.	Essential questions, very accurate claims, very valid /strong /accurate evidence, and very meaningful reflection.
Very weak or No connections between questions, claims, and evidence.	Weak connection between questions, claims, and evidence.	Moderate connections between questions, claims, and evidence.	Strong connection between questions, claim, and evidence.	Very strong connection between questions, claims, and evidence even though students do not follow the order of the SWH template.
Do not flow smoothly from one area to another.	May not flow smoothly from one area to another.	May flow smoothly from one area to another.	Flow nicely from one area to another.	Flow very nicely from one area to another.
Student generate untestable question.	Student generate single testable question.	Student generates a few testable questions.	Student understands the whole ideas and generates multiple testable/meaningful questions.	Student catches the essence of the investigation thoroughly, and generates multiple testable/significant questions.
No use of data to justify claims.	Minimal use of data to justify claims.	Student may acknowledge why his or her observation/data happened.	Student acknowledges why his or her observation/data happened through their claims and evidence.	
Student proposes invalid/no claims.	Student proposes invalid claims.	Student may propose valid claims.	Student proposes valid/accurate/high quality of claims.	Student proposes very valid/accurate/high quality of claims.
Student use only text.	Student use only text.	Student use multiple mode representations but which are not embedded.		
Student shows no understanding.	Student shows very weak understanding.	Student shows understanding of the concept framework.		
Evidence does not support the ideas (claims).	Evidence may not support the ideas.			

Continued…

The Analytical Framework for Evaluating the Quality of Whole Argument in Student Science Writing with the SWH approach

1 – 2	3 – 4	5 – 6	7 – 8	9 – 10
No reflection.	Student may not acknowledge errors.	Evidence supports some of the ideas. Student may develop scientific conceptual understanding. Student acknowledges errors but may not explain them.	Student use multiple mode representations which are embedded (they fit well with the text). Student shows high understandings of the concept framework in their evidence. Student develops scientific conceptual understanding through argument. Students know how they can correct their errors.	Student use multiple mode representations which are embedded. (they fit very well with the text). Student shows enhanced understandings of the concept framework in their claims, evidence, and reflection. Student develops high quality of scientific conceptual understanding through argument. Student explains how they can correct their errors and has new testable questions and applies their learning to everyday life.

APPENDIX E

GRADING RUBRIC FOR THE SECOND SEMESTER GENERAL CHEMISTRY HOUR EXAM-II, PROBLEM NUMBER 20 ON BUFFERS.

Exam-II problem 20 that was also analyzed for this research study was based on the concept of *Buffers* and was a multiple-choice problem.

20. Assume that the standardized aqueous solutions of each of these are available:

Substance	Dissociation Constant
NaF	K_b=1.5x10^{-11}
HF	K_a=6.8x10^{-4}
$CH_3COO^-Na^+$	K_b=5.6x10^{-10}
CH_3COOH	K_a=1.8x10^{-5}
$NH_4^+Cl^-$	K_a=5.6x10^{-10}
NH_3	K_b=1.8x10^{-5}

Answer choice given in Bold is the correct answer choice or the choice that earns maximum possible points.

i. A classical buffer with a good capacity with a desired pH =5.0 would be conveniently prepared by appropriate mixture of_ _ _ _ _ _ _ _ _ _ _ _ _ **(3 points).**

a) HF and NaF

b) $CH_3COO^-Na^+$ and CH_3COOH

c) NH_3 and $NH_4^+Cl^-$

d) CH_3COOH and $NH_4^+Cl^-$

ii. Consider a 1.0 L buffer solution containing 0.15 M HF and 0.25 M NaF.

[Ka=6.8×10^{-4}]. (20 points).

a. Write the principle equilibrium equation for this buffer system. **(2 points)**

b. Calculate the pH of the above buffer solution at 25 °C (Show an ICE table, check your assumptions (if any), and use correct number of sig. figs. for full credit. **(8 points).**

c. What will happen if 0.050 mol of HCl is introduced into the above buffer? Write a chemically balanced equation to justify your answer. **(2 points).**

d. Calculate the pH of the above buffer solution after the addition of 0.050 mole HCl. (Show all the steps for full credit). **(8 points)**

Grading rubrics for problem (ii):

a. Correct principle equilibrium equation for the buffer system (2 points).

⇒ $HF_{(aq.)} + H_2O_{(l)} \rightleftharpoons H_3O^+_{(aq.)} + F^-_{(aq.)}$

⇒ Correct equation without equilibrium arrows and states but correct reactants and products**. (1 point).**

⇒ Correct equation with equilibrium arrows but no or incorrect states indicated. **(1.5 points).**

⇒ Correct equation, no equilibrium arrows but correct states. **(1.5 points).**

⇒ Correct reactants **(0.5 points).**

⇒ Correct products **(0.5 points).**

b. ICE table completely correct (3 points).

⇒ Only initial concentrations correct in ICE **(1 point).**

⇒ Change concentration correct in ICE **(1 point).**

⇒ Ending concentration correct in ICE table **(1 point).**

⇒ If used quadratic equation correctly to find x **(3 points).**

OR

⇒ **Assumption of x<<0.15 M and ignoring x and finding $x=4.1x10^{-4}$ (3 points).**

⇒ **pH=-log ($4.1x10^{-4}$)=3.39 (1 point).**

⇒ **Checking work to find percent dissociation to 0.27% (1 point).**

c.

⇒ Correct explanation of what will happen if 0.050 mols of HCl is introduced into the above buffer **(1 point).**

⇒ Correct equation supporting explanation **(1 point).**

d.

⇒ For the neutralization reaction

⇒ **Correct ICF table (1.5 points).**

⇒ Initial concentration correct **(0.5 points).**

⇒ Change in concentration **(0.5 points).**

⇒ Final concentration **(0.5 points).**

⇒ **For the buffer equation ICE table all correct (1.5 points).**

⇒ Initial concentration correct **(0.5 points).**

⇒ Change correct **(0.5 points).**

⇒ Ending concentration correct **(0.5 points).**

⇒ **Assumption x<<0.20 M ignore x and finding the x to be equal to $6.8x10^{-4}$ (3 points).**

OR

⇒ **using Quadratic correctly to find x (3 points).**

⇒ Using –log ($6.8x10^{-4}$) to find pH=3.17 (**1 point).**

⇒ Incorrect pH though correct use of –log ($6.8x10^{-4}$) **(0.5 points).**

⇒ Check of assumption using percent dissociation equation =0.34% (**1 point).**

APPENDIX F

LABORATORY EXPERIMENT WRITTEN IN SCIENCE WRITING HEURISTIC GUIDED-INQUIRY FORMAT FOR THE EMPIRICAL FORMULA OF COPPER OXIDE

Determining the Identity of a Chemical Reactant

Overview
A bottle containing a red powder is labeled "Oxide of Copper." Heating measured portions of the red oxide of copper in open air results in a chemical reaction. Is the original red powder pure powdered copper metal that has been mislabeled, or some other compound?

Safety
Wear goggles, apron, and gloves. Be careful of hot iron- and porcelain-ware. Dispose of waste as directed by your instructor.

Procedure
To do this analysis, you and your classmates should divide into groups to design experiments, run several experiments, and collect data. Some of you will decide to perform specific experimental runs using different masses of the red powder, others will choose to replicate data. Each person should conduct the experiment at least once. As a group, you should decide what information to tabulate on the chalkboard.

Suggestions for running the experiment:

- Place your ring stand under the hood so that fumes will be drawn away from your experiment.
- Attach an iron ring to your ring stand to support your evaporating dish in a clay triangle.
- Find the mass of a clean, dry evaporating dish (washed, rinsed with distilled water).

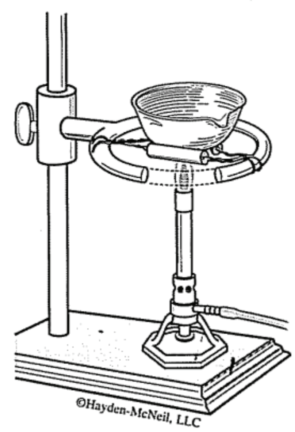


Figure 6-1. A sample is heated in an evaporating dish over a flame from a Bunsen burner. A clay triangle is used to support the evaporating dish. The top of the inside blue flame touches the bottom of the dish.

- Set your Bunsen burner on the base of the ring stand and adjust the height of the iron ring so that the bottom of the evaporating dish rests at the top of the inner blue flame.

  Heat the evaporating dish with nothing in it for two minutes. Allow the dish to cool to room temperature. Obtain the exact mass of the dish. Reheat and repeat this procedure, heating to constant mass.

- Now, add between 1.000 and 2.000 grams of red powder to your evaporating dish and obtain the *exact mass* of this red powder (to four places after the decimal point). Record the mass of the evaporating dish and red powder. Determine the mass of the powder. Heat the red powder so that it completely reacts. What color does the product have? Record this observation in your notebook.

- When you have heated your sample enough to convert it, turn off the burner and allow your evaporating dish and its contents to cool to room temperature. Use crucible tongs to handle the dish. Determine the mass of the product *after* the dish has cooled to room temperature (about five minutes).

- Repeat the heating and cooling until the mass of your product is within 1% of the mass found after the first (or second) heating. Record the *exact* mass of your product in your laboratory notebook.

- Dispose of the product in the labeled jar in the laboratory.

Analysis

How can you determine the composition and chemical name of the red powder, the reactant?

Evaluate your tabulated results with your classmates. You may find it useful to consider the following questions as you conduct your class discussion.

1. What can we learn from the percent by mass composition of the product, copper (II) oxide?
   a. For example, how much copper is in the product (copper (II) oxide) and from where did it come?
   b. How do we know this and why is it important?
   c. What other element is present in the product? From where did it come?
   d. How is the Law of Conservation of Mass involved?
2. How do your results compare with those of your classmates?
3. What claim can you make about the composition of the red powder you used as a reactant—was it a pure copper metal powder, was it just copper ions, or was it another form of copper oxide? How does your evidence support your claim?
4. Working with your classmates, write a balanced chemical equation that represents what happens when the red powder is heated to produce copper (II) oxide. Is this a chemical reaction or a physical process? If it is a chemical reaction, classify the type of reaction.

Post-Laboratory Question

A 2.540 gram sample of an oxide of tin was heated in the air and 2.842 grams of tin (IV) oxide was obtained. What was the formula for the original oxide of tin?

APPENDIX G

LABORATORY EXPERIMENT WRITTEN IN TRADITIONAL FORMAT FOR THE EMPIRICAL FORMULA OF COPPER OXIDE

The Empirical Formula of an Oxide of Copper

Introduction

There have been reports from several lab sections of problems preparing copper sulfate from the copper oxide found in the laboratory. Further investigation of these reports showed that some copper oxide samples were red rather than black. Heating the red powder increases the mass of the powder and a product that is black copper oxide, CuO. Some have argued that the red powder, which was labeled copper oxide, is actually copper powder also known to be red. Others argue that the red powder is not labeled wrong, but is actually a different copper oxide. Your job this week is to determine what the composition of the red powder and if it is an oxide of copper, find the empirical formula for the compound.

Equipment

porcelain evaporating dish
clay triangle
iron ring
ring stand
burner

Materials and Safety Information

Compound	Potential hazards	Precautions to be taken
red powder samples (known to contain copper or a copper oxide)	May cause eye and skin irritation, causes respiratory tract infections.	Wear gloves and goggles, work under a hood, avoid breathing the dust

For more information on safety concerns, go to http://avogadro.chem.iastate.edu/MSDS/.

Waste Disposal

Dispose of the products by pouring them into the proper waste container.

Experimental Procedure

Here is the information you will need. Your teaching assistant will assign you to a group. Each person in the group performs an experiment and contributes results to the group for discussion and use in solving the problem.

1. Use a porcelain evaporating dish as the container to heat the red powder in.

2. Use a sample of the red powder that weighs between 1 and 2 grams.

3. Set the evaporating dish on a clay-triangle, supported by an iron ring attached to your ringstand.

4. Set your burner on the base of your ringstand and adjust the iron ring so the bottom of the evaporating dish is about 2 cm (3/4 inch) above the top of the burner.

5. Light the burner and adjust the gas and air mixture to get a good, hot flame. Your teaching assistant will show you how to do this.

6. Set the ringstand in the hood so any fumes will be drawn out of the lab. Notice the warning on the bottle label about not breathing the dust!

7. Heat strongly for 5 to 10 minutes, then allow the dish to cool to room temperature before weighing.

8. Heat again for 5 to 10 minutes, cool and recheck the mass. If the conversion to copper(II) oxide, CuO is complete the mass should be within 1% of the mass found after the previous heating. If it is not, continue heating, cooling and weighing until two consecutive weighings give masses of product that agree to within 1%.

9. Give your product to your teaching assistant.

Report

- **Answer the following questions:**
  1. Did your powder gain or lose mass?
     - Compare this result to 3 or 4 other groups. Did they all get similar results?
  2. What is the Law of Conservation of Mass (Matter)?
     - Your crucible and its contents changed mass. Where did this mass come from/go to?
  3. Knowing that the final black powder has the formula CuO, what percentage of its mass is Cu and what percentage is O?
     - How many grams of Cu do you have in your black powder?
     - Where did the copper in the black powder come from?
     - How many grams of copper were in the red powder?
     - Is the red powder copper or a copper oxide?
     - What is the number of moles of Cu atoms in the red powder? If the red powder is an oxide, what is the number of moles of O atoms in the red powder?
     - What is the chemical formula of the red powder?
  4. What is the balanced equation for the reaction of the red powder to give CuO (the black powder)?

- The report should include the following sections:
  - Report Cover (download and print from http://avogadro.chem.iastate.edu/ReportCover)
  - Title
  - Purpose
  - Outline of procedure
  - Safety Summary
  - Data/observations
  - Balanced equations
  - Calculations
  - Discussion
  - Answers to questions

- This experiment requires one laboratory period. The report is due at the beginning of the following laboratory period.

APPENDIX H

LABORATORY EXPERIMENT ON THE SYNTHESIS OF BORANE AMINE ADDUCT (HANDOUT C), WRITTEN IN TRADITIONAL FORMAT FOR THE ADVANCED INORGANIC CHEMISTRY (CHEM 401L) LABORATORY COURSE. THE EXPERIMENT WAS PERFORMED BY ALL THE STUDENTS AS THEIR FIRST REQUIRED EXPERIMENT IN THE COURSE

The Borane–Amine Adduct $BH_3:NH_2C(CH_3)_3$

Note: This experiment requires one 4 hour laboratory period.

Compounds containing boron and hydrogen adopt unusual structures that are not observed for the hydrides of the neighboring element carbon. Representative compounds include B_2H_6, B_4H_{10}, B_5H_9, B_5H_{11}, B_9H_{15}, $B_{10}H_{14}$, $B_{10}H_{10}^{2-}$, $B_{12}H_{12}^{2-}$, and many others. Although these species were initially of interest purely for their curious structures, boron hydrides have become important reagents in organic synthesis. Furthermore, the study of their structures provided the foundation for understanding the bonding in metal clusters and carbocations.

Diborane, B_2H_6, is the simplest of the boranes. It is most conveniently prepared from the reaction of sodium borohydride, $NaBH_4$ (frequently called sodium tetrahydroborate), with BF_3 in ether:

$$3\,NaBH_4 + 4\,BF_3 \longrightarrow 3\,NaBF_4 + 2\,B_2H_6$$ (in ether)

At room temperature, diborane is a gas with the molecular structure shown in Figure 4-1.

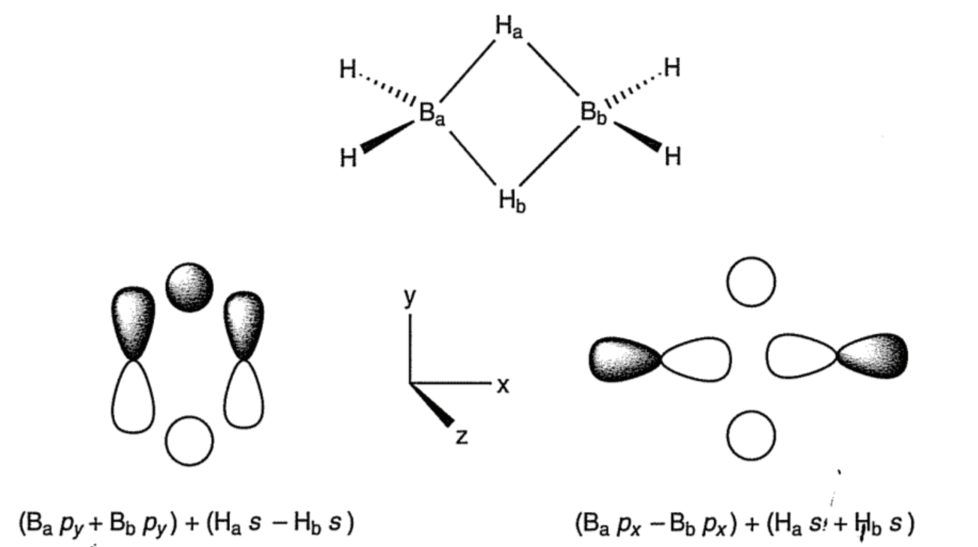


Figure 4-1
Structure of B_2H_6 and the orbitals involved in B–H–B bonding.

The two bridging H atoms lie above and below the plane described by the four terminal H atoms and the two B atoms. Whereas each terminal H atom bonds to only one B atom, each of the bridging H atoms bonds equally to two B atoms. In diborane there are eight B–H bonds, and one might expect that 16 valence electrons are needed to hold the molecule together (normally, a bond consists of an electron pair). Instead, diborane only possesses 12 valence electrons (3 from each boron and 1 from each hydrogen). How are 12 electrons able to form eight B–H bonds? The answer is related to the presence of the bridging hydrogen atoms. The *s* atomic orbitals on these hydrogen atoms overlap with *p* atomic orbitals from both of the adjacent boron atoms to form "multicenter" molecular orbitals as shown in Figure 4-1. The four electrons in these two multicenter molecular orbitals form four B–H bonds, for an average of only *one* electron per bond. The other eight valence electrons in diborane form the normal two-electron bonds to the terminal hydrogen atoms. Such molecular orbitals, consisting of the simultaneous overlap of several atomic orbitals, are common to most of the boron hydrides.

Although B_2H_6 exists largely in the bridged form, it does dissociate to a very small extent to give BH_3.

$$B_2H_6 \rightleftharpoons 2\ BH_3$$

Electron acceptors are sometimes referred to as Lewis acids, and electron donors as Lewis bases. Borane, BH_3, is a Lewis acid because it has six valence electrons and thus can accept two electrons from other molecules. Borane forms numerous complexes (called adducts) with donor molecules such as amines and phosphines. For example, diborane reacts with trimethylamine as shown

$$B_2H_6 + 2\ N(CH_3)_3 \longrightarrow 2\ BH_3{:}N(CH_3)_3$$

The geometry around both the B and N atoms is approximately tetrahedral, and the structure of the adduct is very similar to that of the all-carbon analogue neopentane, $CH_3{-}C(CH_3)_3$.

Historically, Lewis base adducts of borane were prepared from B_2H_6, a substance that inflames in air and is immediately hydrolyzed by water. In addition to these hazards, B_2H_6 is exceedingly toxic. For these reasons, a more convenient and less dangerous route to the adducts was sought. It was found that the reaction of $NaBH_4$, which is an air stable solid, with an alkylammonium salt produces the borane–amine adduct under mild conditions:

$$NaBH_4 + NHR_3{}^+Cl^- \longrightarrow BH_3{:}NR_3 + NaCl + H_2$$

The particular reaction to be carried out in this experiment involves *tert*-butylammonium chloride; this salt may be simply prepared by bubbling gaseous

HCl into an ether solution of *tert*-butylamine:

$$NH_2C(CH_3)_3 + HCl \longrightarrow NH_3C(CH_3)_3{}^+Cl^-$$

The borane adduct is formed according to the following equation:

$$NaBH_4 + NH_3C(CH_3)_3{}^+Cl^- \longrightarrow \underset{\text{m.p (96°C)}}{BH_3\!:\!NH_2C(CH_3)_3} + NaCl + H_2$$

The product, $BH_3\!:\!NH_2C(CH_3)_3$, is a white solid (mp 96 °C) that is stable toward air and water at room temperature. You will measure its IR and ^1H nuclear magnetic resonance (NMR) spectra. The ^1H NMR spectrum of $BH_3\!:\!NH_2C(CH_3)_3$ consists of one sharp peak corresponding to the $-CH_3$ protons at approximately $\delta - 1.2$ relative to tetramethylsilane. The corresponding signals for the protons on the N and B atoms are broadened so greatly by the nuclear quadrupole moments of ^{14}N and ^{11}B that they may not be visible in the spectrum.

Borane adducts undergo many reactions. For example, the replacement of H by Cl in the BH_3 portion of the molecule can be accomplished by reaction with gaseous HCl

$$BH_3\!:\!NH_2C(CH_3)_3 + HCl \longrightarrow BH_2Cl\!:\!NH_2C(CH_3)_3 + H_2$$

This reaction again illustrates the hydridic, H^-, nature of the H atoms attached to the electropositive boron atom. The hydridic H atoms readily combine with protonic, H^+, hydrogen atoms to produce H_2. The analogous reaction with HF replaces all three hydrogen atoms on the boron

$$BH_3\!:\!NH_2C(CH_3)_3 + 3\,HF \longrightarrow BF_3\!:\!NH_2C(CH_3)_3 + 3\,H_2$$

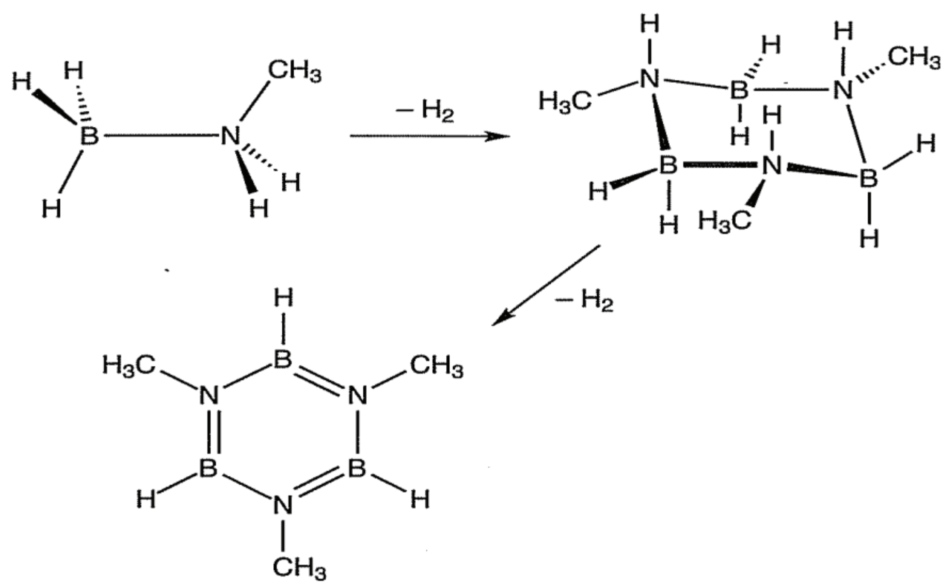
The same adduct can also be prepared directly by treating BF_3 with $NH_2C(CH_3)_3$.

Trialkylamine-boranes react with alkenes to form products in which the B and H have added across the double bond

$$BH_3\!:\!N(CH_3)_3 + 3\,H_2C{=}CHR \longrightarrow B(CH_2CH_2R)_3 + N(CH_3)_3$$

The trialkylborane $B(CH_2CH_2R)_3$ is a sufficiently weak Lewis acid that it may be liberated from the trimethylamine without difficulty. The ability of a borane to add across the double bond of an alkene in an anti-Markownikov fashion is the basis for the widespread use of boranes in organic chemistry.

Borane-amines lose H_2 at high temperatures and generate a variety of products, depending on the particular reactant and the conditions. When the borane-methylamine adduct, $BH_3\!:\!NH_2(CH_3)$, is heated to 100 °C, it yields $B_3N_3H_3(CH_3)_3$, which is the B–N analogue of 1,3,5-trimethylcyclohexane. Further loss of H_2 occurs at roughly 200 °C to produce the unsaturated cyclic ring compound $B_3N_3H_3(CH_3)_3$ called 1,3,5-trimethylborazole:



The carbon analogue of 1,3,5-trimethylborazole is mesitylene, 1,3,5-$C_6H_3(CH_3)_3$. The parent compound borazole, $B_3N_3H_6$, structurally resembles the isoelectronic compound benzene. For this reason, borazole is sometimes called "inorganic benzene." Like benzene, it has a planar hexagonal structure, and the relatively short B–N bonds indicate the presence of B–N π bonding. Despite the physical similarities, benzene and borazole have quite different chemical reactivities. The π system of benzene is relatively inert to addition reactions. In contrast, borazole adds hydrogen halides, HX, to give the saturated cyclic aminoborane $B_3N_3H_9X_3$. The susceptibility of borazole to attack is related to the polar nature of the B–N bond.

EXPERIMENTAL PROCEDURE

Note: In contrast to many hydride compounds, such as NaH, CaH_2, or $LiAlH_4$, which react explosively with water, $NaBH_4$ is stable in neutral or alkaline aqueous solutions. It rapidly hydrolyzes in acidic solution, however. Fresh $NaBH_4$ should be used in this experiment—old samples of $NaBH_4$ will give inconsistent or poor yields.

tert-Butylammonium Chloride, $NH_3C(CH_3)_3^+Cl^-$

In a hood, dissolve 2.5 mL (1.7 g, 23 mmol) of 2-amino-2-methylpropane [*tert*-butylamine, $NH_2C(CH_3)_3$] in 20 mL of anhydrous diethyl ether. Cautiously bubble gaseous HCl from a compressed gas cylinder into the solution until precipitation of $NH_3C(CH_3)_3^+Cl^-$ is complete. Suction filter the product on a medium frit, wash the solid with a few milliliters of ether, and dry the solid in a vacuum. Determine the yield. Although many alkylammonium chloride salts are very hygroscopic, $NH_3C(CH_3)_3{}^+Cl^-$ is not; it need not be stored in a desiccator except when the humidity is high.

***tert*-Butylamine-Borane, $BH_3:NH_2C(CH_3)_3$**

Assemble the apparatus shown in Figure 4-2 and lubricate the stirring shaft bearing with glycerin. The drying tube is necessary only if the atmospheric

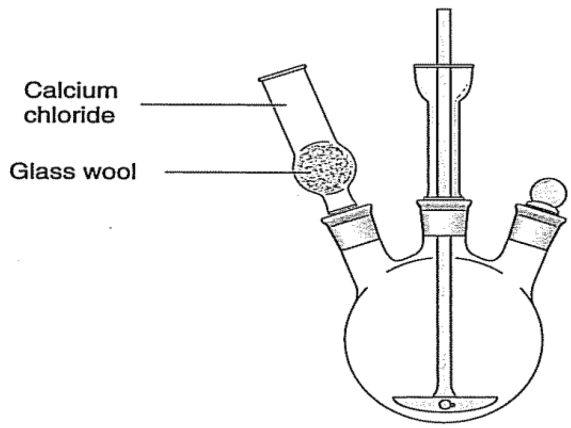


Figure 4-2
Apparatus for preparation of $BH_3:NH_2C(CH_3)_3$.

humidity is very high. Add 1.3 g (11.8 mmol) of $NH_3C(CH_3)_3{}^+Cl^-$ and 15 mL of tetrahydrofuran (THF) to the 250-mL three-neck flask. (The THF may be used as obtained commercially unless it contains large amounts of water. Then it should be dried over NaOH and distilled.) To the stirred suspension, add 0.20 g (5.3 mmol) of powdered $NaBH_4$. At this point, H_2 gas will be evolved. Add an additional 10–15 mL of THF and continue stirring the solution for about 2 h at room temperature. Filter the solution using a suction filtration apparatus (see Fig. 13-1). After the filtration, disconnect the rubber vacuum tubing from the filter flask *before* the water flow is turned off; this action will prevent water from backing up into the trap. Discard the solid (which contains NaCl and unreacted excess $NH_3C(CH_3)_3{}^+Cl^-$) and keep the solution. Using a rotary evaporator, evaporate the THF solution to dryness. The $BH_3:NH_2C(CH_3)_3$ product that remains in the flask is usually of high purity; determine its melting point to confirm this. If the melting range is less than 4 °C, skip the following recrystallization step. If the melting range is greater than 4 °C, the compound should be recrystallized by dissolving it in a minimum amount (1–2 mL) of toluene and adding 20 mL of hexane until precipitation is complete. Collect the $BH_3:NH_2C(CH_3)_3$ by suction filtration and dry the solid product in air. Redetermine its melting point.

Finally, calculate the yield of product. Measure the IR spectrum of the product in $CHCl_3$ or $CDCl_3$ solution.

REPORT

Include the following:

1. Percentage yields of $NH_3C(CH_3)_3^+Cl^-$ and BH_3:$NH_2C(CH_3)_3$.
2. Melting point of BH_3:$NH_2C(CH_3)_3$.
3. Infrared spectrum of BH_3:$NH_2C(CH_3)_3$ with assignments to vibrational modes in the molecule. Compare the B–H, C–H, and N–H stretching frequencies and account for their differences.

PROBLEMS

1. Propose a mechanism for the reaction of $NaBH_4$ with $NH_3C(CH_3)_3^+Cl^-$.
2. Suggest a method of establishing the presence of boron in your product, BH_3:$NH_2C(CH_3)_3$.
3. Earlier it was noted that B_2H_6 inflames in air and rapidly hydrolyzes in water. Write balanced equations for these reactions.
4. Write a balanced equation for the hydrolysis of $NaBH_4$ in acidic solution.
5. Draw structures of the following: $NaBF_4$, $NaBH_4$, $B(CH_3)_3$, and BF_3.
6. Tetrahydrofuran forms an adduct with BH_3, BH_3:THF. Draw the structure of this compound. Is there any evidence from this experiment that would suggest that THF coordinates more or less strongly to BH_3 than does $NH_2C(CH_3)_3$?
7. Account for the fact that $LiBH_4$ is more soluble in THF than is $NaBH_4$. Would you expect $LiBH_4$ or $NaBH_4$ to give better yields in the present experiment? Why?
8. If you wished to carry out a reaction of the type

$$BH_3{:}NH_2C(CH_3)_3 + \text{amine} \longrightarrow BH_3{:}\text{amine} + NH_2C(CH_3)_3,$$

what amine would you choose and what reaction conditions would you use to drive the reaction to completion?

INDEPENDENT STUDIES

A. Prepare and characterize other amine-borane adducts, such as BH_3:$NH(CH_3)_2$ and BH_3:$N(CH_3)_3$. (Nöth, H.; Beÿer, H. *Chem. Ber.* **1960**, *93*, 928. Nainan, K. C.; Ryschkewitsch, G. E. *Inorg. Synth.* **1974**, *15*, 122.)

B. Using your BH_3:$NH_2C(CH_3)_3$, prepare and characterize BH_2X:$NH_2C(CH_3)_3$ (where X = F, Cl, Br, or I). (Nöth, H.; Beyer, H. *Chem. Ber.* **1960**, *93*, 2251. Ryschkewitsch, G. E.; Wiggins, J. W. *Inorg. Synth.* **1970**, *12*, 116.)

C. Prepare and characterize BH_3:py (where py = pyridine) and $[BH_2(py)_2^+]I^-$. (Ryschkewitsch, G. E. *J. Am. Chem. Soc.* **1967**, *89*, 3145. Nainan, K. C.; Ryschkewitsch, G. E. *Inorg. Chem.* **1968**, *7*, 1316.)

D. Determine the mass spectrum of BH_3:$NH_2C(CH_3)_3$ and make assignments to all ion fragments.

E. Prepare the interesting tridentate ligand, hydrotris(1-pyrazolyl)borate, $HB(C_3H_3N_2)_3^-$. (Trofimenko, S. *Inorg. Synth.* **1970**, *12*, 102.)

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